U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-288 939

Modulated Exhaust Gas Recirculation System for Light Duty Diesel Engines

Ricardo and Co Engineers (1927) Ltd, Shoreham-by-Sea (England)

Prepared for

Environmental Protection Agency, Ann Arbor, MI Emission Control Technology Div

Aug 78

United States
Environmental Protection
Agency

Motor Vehicle Emission Laboratory
2565 Plymouth Road
Ann Arbor, Michigan 48105

EPA 460/3-78-007
August 1978

Air

PB 288939

EPA

Modulated Exhaust Gas Recirculation System For Light Duty Diesel Engines

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NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

BIBLIOGRAPHIC DATA SHEET

1. Report No.

2.

PB288939

4. Title and Subtitle
Modulated Exhaust gas Recirculation System for Light Duty Diesel Engines

5. Report Date
August 1978

6.

7. Author(s)
D.A. Pike

8. Performing Organization Rept. No. EPA 460/3-78-007

9. Performing Organization Name and Address
Ricardo and Company Engineers (1927) Ltd.
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10. Project/Task/Work Unit No.

11. Contract/Grant No.
68-03-2465

12. Sponsoring Organization Name and Address
U.S. Environmental Protection Agency
Office of Mobile Source Air Pollution Control
Emission Control Technology Division
Ann Arbor, Michigan 48105

13. Type of Report & Period Covered
Final

14.

15. Supplementary Notes

16. Abstracts

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This report describes a system of exhaust gas recirculation, modulated to reduce the NO_x emission of a Mercedes 300 D light duty diesel vehicle, to within defined limits of other parameters, such as HC and CO emissions, and performance loss, etc. To offset losses in performance due to the application of EGR. A turbo charger was fitted to the vehicle to provide excess air. No extra fuel was supplied.

17. Key Words and Document Analysis. 17a. Descriptors

Exhaust gases
Diesel engines
NO_x emissions
HC emissions
CO emissions

Turbo chargers

17b. Identifiers/Open-Ended Terms

Air Pollution
Automobiles
Emissions

17c. COSATI Field Group

18. Availability Statement
Release Unlimited

19. Security Class (This Report)
UNCLASSIFIED

20. Security Class (This Page)
UNCLASSIFIED

21. No. of Pages
221

22. Price
A10-A01

I

EPA 460/3-78-007

MODULATED EXHAUST GAS RECIRCULATION SYSTEM FOR LIGHT DUTY DIESEL ENGINES

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Contract No. 68-03-2465

EPA Project Officer:
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Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Mobile Source Air Pollution Control
Emission Control Technology Division
Ann Arbor, Michigan 48105

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Publication No. EPA-460/3-78-007

SUMMARY

It has been shown that by the application of a proportion of exhaust gas to the inlet air of a light duty diesel engine the NOx emission in the exhaust can be substantially reduced.

This report describes a system of exhaust gas recirculation, modulated to reduce the NOx emission of a Mercedes 300D light duty diesel vehicle, to within defined limits of other parameters, such as HC and CO emissions, and performance loss, etc. To offset losses in performance due to the application of EGR a turbocharger was fitted to the vehicle to provide excess air. No extra fuel was supplied.

Following performance and emission tests on the vehicle in naturally aspirated and turbocharged build, tests were made to establish critical modes of operation during the 1975 FTP drive cycle. These tests were to determine which, if any, parts of the drive cycle contributed a disproportionately large amount to the NOx emission of the vehicle, thus indicating areas which could be most profitably treated with EGR. The result showed that no such critical areas were present and that the whole of the load and speed range of the engine employed during the FTP would have to be treated in some degree.

A comprehensive test bed calibration of the engine was carried out in both N/A and T/C form with additional tests to establish the response of the turbocharged engine to injection retard. During these calibrations, steady state measurements of gaseous emissions, fuel consumption and exhaust smoke density were obtained and graphical presentations of brake specific emissions and fuel consumption developed.

A system of controlled exhaust gas recirculation to the intake of the turbocharger compressor inlet was devised. The EGR flow rate was determined by the reduction of air flow from that of the standard engine.

Calibration of the engine was carried out with manual control of EGR with curves plotted showing the response of the engine in respect of gaseous emissions, smoke and performance. At high levels of EGR the amount of fuel supplied to the engine had to be restricted in order to maintain inlet manifold temperatures and exhaust smoke within reasonable limits. From the curves produced from the EGR calibration, various hypothetical modulations of EGR were deduced from which variations in gaseous emissions, fuel consumption and exhaust smoke were tabulated. These tabulations were computed to provide synthesised vehicle results.

A second type of EGR valve was developed allowing a method of matching some of the synthesised EGR modulations. This system consisted of a mechanical linkage to modify the lifting of a poppet type valve. The linkage was actuated by direct connection to the engine fuel pump control giving a load sensitive variation of EGR. Some measure of speed sensitive control was available by using exhaust gas pressure to modify the valve lift. Computations from test bed results obtained with various builds of this system indicated that the target constraints of the contract could be achieved.

The engine was then re-installed in the Mercedes 300D vehicle complete with EGR system and tests carried out to verify the synthesised results obtained on the test bed. It was shown that 0.4 gpm NOx could be achieved, at the expense of exceeding the legislated limits of HC and CO emissions, with the aid of modulated EGR and injection retard. 1.0 gpm NOx was achieved with standard injection timing and less EGR, with HC and CO emissions within the legislated limits. At all levels of EGR particulate emissions were adversely affected, as were fuel economy, performance and drive-by noise.

SUMMARY OF VEHICLE TEST RESULTS

Vehicle Build	Gaseous Emissions gpm			Part	Fuel mpg (US)		Noise dBA	Acceleration Seconds (mph)		
	HC	NOx	CO	gpm	CVS	HEFT		0-40	0-60	20-60
As-received	.183	1.66	.94	.8	24.3	29.95	74.2	9.6	21.2	18.7
Turbocharged	.14	1.75	.94	.5	23.8	25.6	74.5	9.9	22.4	19.2
EGR Modulation G	.395	.528	2.408	1.11	19.47	24.94	78.0*	10.6	23.5	20.1
EGR Modulation C+	.382	.471	2.379	-	19.95	-	-	-	-	-
EGR Modulation C+ 7° Retard	4.974	.32	6.129	.93	17.15	-	-	11.6	28.6	22.8
EGR Modulation C+ 4° Retard	1.053	.379	2.956	1.228	18.86	24.43	76.2	11.0	25.3	22.4
EGR Modulation D	.226	.961	1.563	1.59	20.08	25.78	-	10.2	22.6	19.1
EGR Modulation D- (7 mm lift)	.245	1.004	1.392	-	20.17	-	-	-	-	-
EGR Modulation D- (2 mm lift)	.171	1.52	1.329	.964	20.28	25.87	76.4	9.4	20.5	19.1

* Artifically high noise level - no retest figure available.

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1. GENERAL INTRODUCTION

This report is an account of work carried out by Ricardo and Company on behalf of EPA, under contract 68-03-2465, to investigate the effects of modulated exhaust gas recirculation (EGR) to reduce the oxides of nitrogen (NOx) in the exhaust of a light duty diesel vehicle.

EGR has been demonstrated by Ricardo and other researchers to be effective in reducing NOx in internal combustion engine exhaust gasses, due to the combined effects of lowering the cycle temperature and diluting the oxygen available for combustion. It has also been demonstrated by Daimler Benz and reported to EPA in 1973 that with high levels of EGR a 147 CID diesel engine can meet the 0.4 gpm limit, although with serious loss of performance and unacceptable smoke due to shortage of oxygen in the cylinder charge.

The purposes of the work detailed in this report were to design, develop and demonstrate a modulation system for EGR to obtain the best practical reduction in NOx formation. A turbocharger was used to attempt to minimise any loss of performance due to the EGR and the ratio of EGR was to be applied preferentially during the operational modes shown to contribute a disproportionately large amount of NOx when measured during the driving cycles of the Federal Test Procedure (FTP) for Light Duty Vehicles (LDV).

For the purposes of these tests a Mercedes 300D LDV was loaned by Daimler Benz and with this vehicle the base line emission characteristics were established. The engine was subsequently installed on a test bed and its EGR response determined before re-installation in the vehicle chassis together with a developed modulated EGR system. The rate of application of EGR was capable of being varied by exchange of parts to match various constraints laid down in the contract. The levels of emissions obtained from the test bed were processed by computer to provide synthesised vehicle results which were subsequently compared on the actual vehicle by running CVS tests (1975 FTP) under the same EGR conditions.

2. OBJECTIVES OF TEST PROGRAMME

The ultimate objectives of the test programme were to reduce the NOx emissions of the LDV by modulated application of EGR by various degrees while maintaining other performance and emissions parameters such as HC, CO, fuel consumption, exhaust smoke and power within defined limits. These objectives were preceded by base level tests of the vehicle and engine without EGR, both naturally aspirated and lightly turbocharged.

In order to best achieve these objectives the test programme was divided into a number of tasks each representing a different aspect of the work. The title and definition of each task was defined in the Ricardo Technical Proposal (Ricardo Note SN.20852) and were as follows:

Task 1 - Replicate Baseline Vehicle Tests

With the vehicle in the 'as-received' condition, tests would be carried out according to the 1975 FTP for LDV and EPA Highway Fuel Economy Tests (HFET). Gaseous emissions were to be recorded using the CVS-CH system and fuel consumption calculated for both FTP and HFET cycles. Additional runs were to be made of the FTP cycle to enable exhaust smoke and particulate levels to be obtained.

Vehicle performance would be established by carrying out simple acceleration tests on a level road to record 0-40 mph, 0-60 mph and 20-60 mph times.

Drive-by noise levels would be established and a subjective assessment of idle noise carried out.

These tests were to be repeated to provide replicate baseline data.

Task 2 - Replicate Baseline Vehicle Tests with Retrofitted Turbocharger

The turbocharger would be fitted with exhaust wastegate adjusted to give a boost pressure suitable for the engine subject to the manufacturers advice. No extra fuelling was to be provided.

The tests carried out in Task 1 above would be repeated with this turbocharged version of the vehicle and the results compared.

Task 3 - Identification of Critical Operating Modes

For this task, instrumentation would be fitted to the fuel injection pump to enable load recordings to be made continuously during the FTP, simultaneously with continuous recording of HC, CO, NOx and exhaust smoke.

The analysis of these results would be used to determine the level and frequency of occurrence of modes contributing significantly to the vehicle NOx emission.

These data would be submitted to the Project Officer for approval.

Task 4 - Dynamometer Tests to Assess Engine Performance at the Selected NOx Producing Modes

The engine would be installed on a test bed coupled to a swinging field dynamometer to provide both motoring and load absorbing capacity. This would enable both drive and overrun conditions to be simulated.

Instrumentation would be provided for the measurement of all functions including temperatures, air flow, fuel flow etc., and analytical equipment would be provided for the measurement of gaseous emissions under steady state conditions.

The engine would be calibrated at the critical modes established in Task 3 above in both N/A and T/C forms and the results presented in graphical form.

At this point in the programme load/speed emissions maps would be obtained at a number of injection timings to establish a possible modified load/speed timing schedule to achieve the lowest combined HC and NOx emissions.

Task 5 - Design, Fabrication and Application of the Variable EGR System

Tests would be run to establish the effect of EGR flow on NOx, HC, CO and smoke at the selected modes of operation. The EGR valve design would be such that the flow rate of EGR could be controlled manually while the engine response was established. A control system would be devised based on the required response of EGR flow to engine operating modes. Computer simulation would be used to assess the modulated results in terms of vehicle emissions and means of adjustment of the EGR valve would be made in response to load and speed signals from the engine as required. The EGR system would be capable of being installed within the existing sheet metal boundaries of the vehicle and would operate independently of external power supplies.

Task 6 - Key Mode Tests with Combined Modulated EGR and Optimised Injection Timing

The EGR system would be tested at the key modes on the T/C engine with brake specific NOx, CO, HC and fuel consumption documented. Tests would be carried out to establish the EGR and timings to conform to the following constraints.

1. Lowest NOx while maintaining other performance parameters such as HC, CO, CO_2 and exhaust smoke with minimum trade offs.
2. Minimised NOx emissions with no more than an estimated level of 0.41 gpm HC.
3. Minimised NOx emissions with the only constraint being the retention of 85% of the peak bhp of N/A engine.
4. NOx emissions of 0.3-0.4 gpm if 2 and 3 are estimated to result in lower than 0.4 gpm NOx.
5. The EGR level estimated to achieve 1.0 gpm NOx.

The effects of injection retard would be established during these tests. Throughout these tests the general behaviour of the engine would be observed with subjective assessment of noise. Full documentation of engine settings would be made as these would be required for reproduction of the same conditions for Task 7.

Task 7 - Testing and Assessment of EGR System Installed in the Vehicle

The engine, complete with modulated EGR system and turbocharger, would be removed from the test bed and re-installed in the vehicle, together with such instrumentation as would be necessary to ensure accurate setting of the EGR and injection timing.

Re-adjustment of the EGR/timing systems to minimise any remaining adverse effects of EGR on transient operation were to be carried out as necessary.

Replicate 1975 FTP and HFET tests would be carried out on the vehicle with EGR and injection timings as established in Task 6 above.

At each setting the vehicle would be tested in the same way as in Tasks 1 and 2 for the original vehicle baseline data.

3. EQUIPMENT AND APPARATUS

3.1 Details of Test Vehicle

Daimler Benz Mercedes 300D Light Duty Diesel Vehicle (USA version).
Model No. 213130
Automatic transmission
4000 lb inertia weight

The vehicle is illustrated in Figure 1.

3.2 Test Bed Engine

(Removed from the above vehicle.)

Engine type designation, OM 617
Five cylinder, 91 mm bore x 92.4 mm stroke
3.005 litres capacity
Indirect injection using Daimler-Benz pre-chamber combustion system
Fuel injection by Bosch using nozzles type DNOSD 220.
Turbocharger (when fitted), Garrett AiResearch Model T3.

3.3 Analytical Equipment

3.3.1 Gaseous Emissions (Vehicle Tests)

HC emission measured by IPM heated flame ionisation detector (FID), via heated sample line (180°C). CO measured by infra red gas analyser (IRGA). NO and NOx emissions measured by chemiluminescence analyser.

3.3.2 Gaseous Emissions (Test Bed)

For test bed operation portable apparatus was used such as is shown in Figure 2. HC and CO emissions were measured as above; NO emission was measured by IRGA.

3.3.3 Particulate Emissions

Particulate emissions were measured on the vehicle using a Ricardo particulate development tunnel (Reference 1). Figure 3 illustrates this apparatus.

3.3.4 Exhaust Smoke

For vehicle tests a full flow US PHS obscuration smoke meter was used and pen recordings were made of smoke opacity over the 1975 FTP drive cycle.

For test bed use exhaust smoke density was assessed using the Bosch sample method. By this system an exhaust sample is drawn through a filter paper which is measured by a light meter to a scale of 10. Comparison of the two methods are to be found in Reference 2.

3.3.5 Noise Tests

Vehicle noise was assessed using Bruel and Kjaer portable sound level meter type 2203 under SAE drive-by conditions to J986a.

Test bed noise and vehicle idle noise were assessed subjectively.

3.4 Instrumentation

3.4.1 Vehicle

The vehicle was equipped to record the following:

Engine revolutions
Maximum cylinder pressures
Injection pump linkage movement (see section 6)
Exhaust temperature.

3.4.2 Test Bed

Normal test bed instrumentation was used including the automatic control of oil and water temperatures.

Additional instrumentation was used to record the following:

Maximum cylinder pressures as above.

Nozzle needle lift for dynamic injection timing
Injection pump linkage movement as above
Inlet air flow
Exhaust smoke density
Gaseous emissions.

3.5 Fuel

The diesel fuel used for the vehicle tests is specified in appendix II.

4. TASK 1 - REPLICATE BASELINE VEHICLE TESTS

4.1 Introduction to Task 1

A United States' version of the Mercedes 300D vehicle was delivered in standard build from normal production sources. It was necessary to carry out initial tests in the 'as-received' build in order to establish the baseline level of emissions, performance, smoke density and fuel consumption of the vehicle. This was carried out under Task 1 of the programme.

4.2 Test Procedure - Task 1

Before test work commenced, the exhaust outlet of the vehicle was adapted to enable connections to the Ricardo emissions laboratory apparatus to be made. In addition, provision was made to enable exhaust manifold temperature and engine revolutions to be recorded. It was also necessary to provide facilities for measuring the maximum pressure in the pre-chamber of the engine as a precaution against causing excessive pressures to occur when the turbocharger, called for in Task 2, was installed.

The vehicle speedometer was calibrated and the following tests carried out:

1. 1975 FTP tests for gaseous emissions
2. EPA HFET
3. Exhaust smoke obscuration tests over the LDV cycle
4. Particulate emissions measurements over the LDV cycle
5. Noise performance assessment consisting of acceleration times for 0-40, 0-60 and 20-60 mile/h.

Replicate tests were to be carried out on the above to ensure consistency of results.

4.3 Test Conditions - Task 1

Before carrying out items 1, 3 and 4 above the vehicle was pre-conditioned as required for the 1975 FTP to enable cold starts to be obtained.

Vehicle conditions: Mercedes 300D standard US build.
Inertia weight 4000 lb
Road load set to 13.2 bhp at 50 mph.

4.4 Test Results - Task 1

Tabulated below are the replicate test results from the base line assessment of the vehicle. Also shown are published results (Reference 3) obtained by Daimler Benz for comparison, where applicable.

	Ricardo Tests			Published D/B Results
Emissions 1975 FTP	Test 1	Test 2	Mean	(Reference 3)
HC gpm	0.189	0.176	0.183	0.229
NOx gpm	1.671	1.654	1.660	1.550
CO gpm	0.943	0.929	0.940	1.430
Particulates gpm	0.775	0.832	0.804	
Fuel Economy				
CVS test mpg (US)	24.77	23.88	24.30	23.9
Highway test mpg (US)	28.96	30.94	29.95	32.4

Vehicle Performance	Ricardo Tests Mean	Published D/B Results (Reference 3)
Acceleration time sec.		
0-40 mph	9.6	
0-60 mph	21.2	19.0 (0-62 mph)
20-60 mph	18.7	
Drive-by Noise (SAEJ986a)		
30 mph low gear	74.2 dBA	

Exhaust Smoke

Exhaust smoke was assessed under FTP conditions by pen recording the output from a US PHS obscuration smokemeter. The resulting traces showed a peak instantaneous level of 20% occurring at times of rapid acceleration from cold, reducing to 10% when hot. At idle the level of smoke was averaged at 6% and at high speed cruise conditions 4% was recorded. Observation of the vehicle exhaust from a following vehicle under normal road conditions revealed no excessive emission of smoke, although the exhaust was visible at idle and during hard acceleration.

The Daimler Benz figures quoted above were obtained at an inertia weight of 3500 lb, using a similar vehicle. In addition to the above test results, pen recordings were made of gaseous emissions, engine revolutions, exhaust temperature and road speed over the FTP driving cycle.

Cylinder Pressures

As an additional test, maximum pressures were measured in the engine pre-chambers using a calibrated Kistler 601 transducer fitted to a dummy heater plug. These measurements were necessary because a limitation on the maximum permissible pressure had been imposed by Daimler Benz to avoid possible damage to the engine when the turbocharger was used for Task 2 tests. The use of a transducer placed in the heater plug position provided a means of estimating the actual pressure over the piston, but obviated the necessity of drilling the cylinder head to obtain direct measurements of over the piston pressure.

The pressures recorded were 62 bar at maximum torque speed (38 rev/s) and 72 bar at maximum power speed (67 rev/s). These figures compared with a limit, suggested by Daimler Benz for the turbocharged engine, of 64 bar over the piston. Much later, during the EGR calibration of Task 5 it transpired that this figure was a mis-interpretation, the correct figure being 85 bar.

4.5 Discussion of Results - Task 1

The results of the gaseous emissions tests showed levels of CO and NOx typical of those for light duty diesel vehicles and a level of unburned HC emissions (at .183 gpm) considerably lower than average (typically .4 gpm). The figures achieved were in good agreement with those published by Daimler Benz on a similar vehicle.

The computed fuel consumption figures were also typical of those obtained from diesel vehicles and in good agreement with published results as was the acceleration time for 0-60 mph of 21.2 seconds.

Drive-by noise level of 74.2 dBA achieved under SAEJ986a conditions (30 mph low gear) was not excessive for a diesel vehicle of this class. From experience it is expected that the diesel engine may have contributed perhaps 1.0 dBA to the noise level over that of an equivalent gasoline vehicle.

The level of exhaust opacity measured while driving the 1975 FTP cycle showed that no severe peaks of smoke output occurred and this was confirmed on the road by visual observation. Although some smoke was visible on hard acceleration and at idle this was not considered objectionable.

Particulates, measured during the 1975 FTP cycle using the Ricardo developed measuring apparatus (Reference 1), showed an emission of 0.8 gpm. This was considered slightly high for this type of vehicle and considerably higher than for an equivalent gasoline powered vehicle.

The results of additional tests to establish the peak pressures showed that with levels in the pre-chamber of 72 bar at full load and speed, the pressures over the piston would have approached the original limit of 64 bar imposed by the engine manufacturers with only a relatively low level of turbocharging in Task 2. The increased pressure limit came too late to allow this to be considered when establishing the level of turbocharging to be applied in Task 2.

4.6 Conclusions - Task 1

The tests carried out under Task 1 of the programme were satisfactory and the results of the emissions, performance and fuel consumption tests were in good agreement with those published for a similar vehicle.

Tests carried out to assess drive-by noise and particulate emissions produced results typical for diesel passenger cars.

5. TASK 2 - REPLICATE BASELINE VEHICLE TESTS WITH RETROFITTED TURBOCHARGER

5.1 Introduction to Task 2

In order to offset the adverse effects on the performance of the vehicle when EGR is applied during later tests, a turbocharger was fitted to the engine. The purpose of the turbocharger would be to provide excess air and no extra fuel would be supplied.

The evaluation of the effects of retrofitting the turbocharger to the engine was assessed on the Mercedes 300D vehicle as Task 2 of the programme.

5.2 Turbocharger Installation

The turbocharger was retrofitted to the engine using manifolds supplied by Daimler-Benz. It was found, however, that the location of the air conditioning pump prevented the turbocharger from being installed on the engine in the position indicated by the manifolds. To overcome this problem both inlet and exhaust manifolds were modified by displacement of the exhaust flange and inlet pipe boss by approximately 1 inch, rearward. In addition the turbocharger inlet pipe supplied by Daimler-Benz could not be used as insufficient clearance existed between the inlet and air conditioning pump. This problem was overcome by the manufacture of a special inlet pipe which could be accommodated in the space available and which was used in conjunction with the original air cleaner and not the larger one supplied.

The exhaust system used for the turbocharger was initially that used for the N/A engine. For later tests a single silencer was used in place of the two used for the standard N/A build. No change was made to the fuel injection system.

5.3 Test Procedure - Task 2

Tests were carried out on the vehicle in the same way as those carried out for Task 1 of the programme. Before emissions and other tests were attempted however it was necessary to evaluate the firing pressures, as described in Task 1, with various builds of the wastegate boost regulator valve of the turbocharger.

Firing pressures were obtained by running the vehicle on the chassis dynamometer at full load over the engine speed range, using intermediate gears where necessary, and reading peak pressures on an oscilloscope using a calibrated Kistler 601 pressure transducer. Of necessity these measurements had to be very brief as it was not possible to maintain full load for long periods on the chassis dynamometer.

5.4 Test Conditions - Task 2

Pre-conditioning of the vehicle was carried out before the appropriate tests as for Task 1.

Vehicle conditions: as-received plus Garrett AiResearch T3 turbocharger with wastegate boost control.

Test conditions for vehicle were as for Task 1.

5.5 Test Results - Task 2

Initial runs were made with the turbocharger in its 'as-received' build. Of prime importance from these results was the effect of boost air on the maximum firing pressure in view of the limit imposed by Daimler-Benz. First results showed that at the maximum power speed of 67 rev/s a boost pressure of 0.6 bar was obtained giving a peak pre-chamber pressure of 96 bar compared with a naturally aspirated peak pressure of 72 bar. At these conditions turbine entry pressure and exhaust back pressure were excessive, caused by the use of the vehicle standard exhaust system of two silencers in series. Removal of the silencers reduced the pressures to a more acceptable level while maintaining the boost at 0.6 bar. Under these conditions maximum pre-chamber pressure increased slightly to 99 bar. This pressure was unacceptably high and the turbocharger wastegate was modified by fitting the lightest spring available to reduce the boost pressure. With this lower rated wastegate spring the boost pressure was reduced to 0.25 bar at the maximum power speed with a pre-chamber pressure of 82 bar and an unsilenced exhaust system. The results of these investigations are shown in Figure 4.

It should be remembered that at the time of these tests it was understood that the maximum peak pressure should not exceed 64 bar over the piston (say 74-76 bar in the pre-chamber), a condition imposing a relatively low level of boost pressure. Even so this low level of boost resulted in an observable deterioration in the vehicle performance in respect of acceleration time, NOx emission and smoke level as will be shown below! The virture of the turbocharger in relation to the constraints imposed by the contract 'scope of work' document was, at this time, being questioned and the relaxation of the cylinder pressure limit to 85 bar by further increase in boost with no change in the fuelling level would have worsened vehicle performance still more.

With the exhaust system used for these tests, i.e. without silencers, the vehicle was unacceptably noisy and the larger of the two silencers was refitted. A brief run was made to examine the effect of this change on the boost at maximum power speed. This was found to have reduced the boost from 0.25 to 0.2 bar (2.9 lb/in^2). Cylinder pressures were not measured under these conditions but it was considered unlikely that any significant change would have occurred. The noise of the vehicle was acceptable under these conditions and all vehicle tests were carried out with this arrangement.

Following the establishment of the build for the turbocharged version of the vehicle, replicate tests to assess performance, emissions, fuel consumption and noise were carried out as for Task 1. The results of these tests are tabulated below with Task 1 results shown for comparison.

	Turbocharged Task 2 Results			As-Received Task 1 Results
Emissions 1975 FTP	Test 1	Test 2	Mean	
HC gpm	.141	.14	.14	.183
NOx gpm	1.773	1.72	1.75	1.66
CO gpm	1.032	.849	.94	.94
Particulates gpm	.498	.501	.5	.8

	Turbocharged Task 2 Results			As-received Task 1 Results
	Test 1	Test 2	Mean	
Fuel Economy				
CVS test mpg (US)	24.15	23.48	23.8	24.3
Highway test mpg (US)	25.3	25.83	25.6	29.95
Vehicle Performance				
Acceleration time seconds			Mean	
0-40 mph			9.9	9.6
0-60 mph			22.4	21.2
20-60 mph			19.2	18.7
Drive-by Noise Test (SAEJ986a)			Mean	
30 mph (low gear)			74.5	74.2 dBA

Exhaust Smoke

Pen recordings of exhaust smoke opacity obtained from the US PHS smokemeter during the 1975 FTP test procedure showed a peak level of 25% during hard acceleration from cold reducing to 15% when hot compared with 20% and 10% for the as-received tests. At idle the smoke level recorded was 7% and at high speed cruise conditions 4%, much the same as the earlier tests without the turbocharger fitted.

In addition to the above results, pen recordings of gaseous emissions, engine revolutions, exhaust temperature and road speed were made for further reference as in Task 1.

5.6 Discussion of Results - Task 2

These results show the turbocharger to have had a deleterious effect on the vehicle performance, the most notable being poorer fuel economy obtained during the highway test. Of the gaseous emissions the slight increase in NOx level over the naturally aspirated version is compatable with the higher maximum firing pressures observed with the turbocharger. It can also be seen that the HC level is reduced with the turbocharged version of the vehicle. In general the overall performance of the vehicle has deteriorated slightly being one second slower accelerating from rest to 60 mph. This slight deterioration in performance was not altogether unexpected as by not providing extra fuel to make use of the excess air supplied by the turbocharger, its presence becomes largely parasitic.

The slight increase in exhaust smoke density under accelerating conditions, may have also been accounted for by the above factors. However, the level of exhaust smoke observed under road conditions, although slightly higher than for the naturally aspirated version of the vehicle, was not considered excessive. An improved particulate emission was recorded during CVS test cycle.

Drive-by noise levels measured under SAEJ986a conditions were unchanged from those obtained in Task 1.

To hold the original cylinder pressure limitation of 64 bar necessitated a low level of boost which in itself resulted in some deterioration in both vehicle and test bed performance, the latter being ascertained in Task 4. The higher cylinder pressure limitation came to light when the engine had been removed from the vehicle and was being operated on test bed EGR work in Task 5. At that time it was decided not to revert to the vehicle and explore increased boost pressure, particularly as the vehicle performance would have deteriorated still further.

5.7 *Conclusions - Task 2*

The results from Task 2 completed the baseline assessment of the 300D vehicle in N/A and T/C builds. From these results it can be concluded that with the low level of boost employed the turbocharger had only minor (mainly detrimental) effects on the vehicle performance, particularly highway fuel consumption. These effects were largely due to the parasitic nature of the turbocharger when no extra fuel is supplied.

6. TASK 3 - IDENTIFICATION OF CRITICAL OPERATING MODES

6.1 Introduction to Task 3

In order that the NOx level of the Mercedes 300D vehicle should be effectively reduced by exhaust gas recirculation it was necessary that the 1975 FTP drive cycle emissions results should be closely examined for critical operating modes. These modes are defined in this sense as those transient phases of the drive cycle which contribute a disproportionately large part of the total mass emission.

6.2 Test Procedure - Task 3

In order that the critical modes of operation could be subsequently reproduced on the test bed, an essential element in the assessment of these modes on the vehicle was to obtain a signal proportional to the fuel delivery to the engine. To this end it was proposed to instrument the fuel injection pump with a transducer to record the fuel rack position. In the event it proved impossible to achieve this on the vehicle and a secondary, more simple, system of instrumentation was devised. This was achieved by attaching a transducer, consisting of a linear characteristic rotary potentiometer, to the fuel pump control linkage. Although this control linkage was not rigidly coupled to the injection pump fuel control rack (being connected via the governor linkage) it was considered that, with the type of idle and over-speed governor being used under these particular conditions, there would be a direct link proportional to fuelling. (Verification of this assumption was made during a later section of the programme when the engine was installed on the test bed.) The installation of the transducer on the fuel pump control linkage is shown in Figure 5.

Further preparation to enable the critical mode data to be obtained consisted of measuring the delay time caused by the various sample lines to the gas analysers. These times were obtained by injecting a suitable gas into the sample lines and measuring the time required for a particular analyser to respond. In addition it was necessary to synchronise each of three emission chart recorders currently in use with respect to the vehicle data recorder.

Following these preparations, replicate tests were carried out using the turbocharged version of the vehicle and the following chart recordings obtained under the 1975 FTP conditions:- engine revolutions, road speed, injection pump linkage position, exhaust temperature, dilute HC, raw HC, dilute CO, dilute CO_2, dilute NOx, raw CO, raw CO_2 and raw NO. From these results selected traces were redrawn by hand on to a common base, taking account of the various delay times and making due allowance for the phase differences of the various recording pens.

As the particular interest is in the dilute NOx level this was selected as the main function which has been drawn in comparison with dilute CO_2, pump linkage position and engine revolutions. These latter parameters were chosen because, of the various separate traces studied, it appeared that there may have been a relationship between them and the NOx emissions.

The CO_2 is of course related to the fuel input level and the relationship of the former to the fuel injection pump linkage position is therefore of some major interest. Figures 6-9 show a reproduction of the composite trace for the above noted four functions. The pen recordings of the raw (undilute) emission constituents, although not of use for this critical modes exercise, were retained for later use to help establish the validity of the test bed emission levels.

6.3 Analysis of Results - Task 3

To attempt to establish a relationship between the NOx emissions and the other parameters shown in Figures 6-9 the traces were analysed by plotting the NOx levels of each transient peak of the drive cycle against a) injection pump linkage position, and b) linkage position x engine revolutions. Figure 10 shows the first of these plots for the cold transient phase of the FTP cycle only, and it can be seen that only a very indistinct relationship exists. On reflection it was realised that NOx increases, broadly speaking, with both load (linkage position) and engine speed, that is with power, and that correlation with either of these parameters individually was unlikely. The obvious seemed to be to relate NOx to the combined functions as being proportional to power output and this proved to give a more positive and distinct relationship as can be seen in Figures 11, 12, 13 where all three phases of the drive cycle are included.

The possibility of using such a combined relationship to form the basis of an exhaust gas recirculation control system to reduce the NOx level is the object of later tests.

One of the aims of the programme was to reduce the weighted NOx levels to as low a g/mile as possible. In order to assess the magnitude of the NOx reduction required it was necessary to calculate the weighted level of the existing trace in g/mile. This was achieved by establishing the area under the NOx line of the trace shown in Figures 6-9 and calculating the mean levels of NOx in ppm for each of the three phases of the FTP cycle and thus obtaining the weighted g/mile. This figure was next proportioned separately for each phase for various levels of NOx in g/mile to produce mean levels in ppm which can be related to those of the pen recordings. These calculations are shown in the table below.

		Calculated NOx Mean Level ppm		
NOx	g/mile	Cold Transient	Stabilised	Hot Transient
Current calculated level	1.8	63.1	37.4	59.8
Reduced level	1.0	35.2	20.9	33.6
Reduced level	0.5	17.6	10.5	16.8
Target level	0.4	14.1	8.4	13.4

It is to be noted that the correlation between the NOx mass emission calculated from the dilute trace included in this note and the measured vehicle result (1.75 g/mile) obtained in Task 2 is excellent.

From these calculations it is shown that to achieve NOx emissions of 0.4 or 0.5 g/mile the level must be reduced throughout the drive cycle to near or below that which is currently recorded when the engine is at idle, i.e. 15, 15 and 14 ppm respectively for each of the three phases of the FTP cycle.

6.4 Critical Operating Modes

Considering the critical modes as being those transients which contribute a disproportionately large part of the total mass emission, it is clear by studying the NOx trace in Figures 6-9 that no individual modes qualify. Therefore the original precept, that low emissions will be obtained by attacking limited areas of the operational load range of the engine, is largely untenable. Rather it seems that considerable areas in the low to average working range will have to be attacked with EGR in order to effect any significant reduction. This is not altogether unexpected as the FTP in itself is formulated to give a mass emission related to a time area integration, where isolated localised peaks will have but little effect on the overall result.

Examination of the traces show that the peaks of the NOx are formed during the acceleration of the vehicle and the levels achieved are largely proportional to a combined function of fuel input and engine revolutions, i.e., power output, as would be expected.

Furthermore, from the formula for the calculation of the weighted mass emissions of NOx; as defined in the Federal Register Vol. 41 No. 164 p.35,650.

$$Y_{WM} = \frac{(0.43\ Yct + 0.57\ Yht + Ys)}{7.5}\ \text{g/mile}$$

it is apparent that the cold and hot transient phases of the FTP each, in broad terms, contribute only about a quarter of the weighted g/mile figure despite these phases containing the highest NOx levels in their individual peaks. The stablised phase of the test on the other hand, contributes one half of the total mass where the phase consists almost entirely of part load, light duty modes. Here again this is evidence of the significance of the contribution from the average operational condition.

From the test evidence, together with the above analytical considerations it is considered that the greatest benefit to a reduction in the weighted NOx output would be achieved by attention to the lighter duty areas of the load range. This approach would have an advantage in that the localised high load peaks of the cold and hot phases of the cycle would be subject to relatively less treatment with EGR, therefore minimising any deterioration in engine performance on this account.

6.5 Conclusions - Task 3

To summarise, it was considered that no individually identifiable critical modes of operation existed and that it would be necessary to treat the whole of the test cycle with EGR to some extent if the low levels of NOx envisaged were to be attained. This would be most advantageously achieved by applying a maximum EGR level at idle with reducing percentage as speed and load are increased in order to limit loss of performance and smoke deterioration.

A method of controlling the exhaust gas recirculation from load and speed parameters would be devised with amounts of gas flow to be determined on the test bed. Any system devised for control of the exhaust gas recirculation would be capable of installation on the vehicle.

7. TASK 4 - DYNAMOMETER TESTS TO ASSESS ENGINE PERFORMANCE AT THE SELECTED NOx PRODUCING MODES

7.1 Introduction to Task 4

From the conclusions of Task 3 above it will have been noted that no identifiable critical modes of operation exist and that the whole FTP drive cycle would require EGR treatment to achieve the lowest NOx targets. It was evident therefore, that Task 4 was to be more complex than the title suggests, it being necessary to assess the engine performance over the whole load and speed range covered in the drive cycle. To this end the engine was removed from the 300D vehicle and installed on a test bed for a full and complete calibration of both naturally aspirated and turbocharged versions.

7.2 Engine Installation

The Mercedes 300D engine (designated OM617) was installed on the test bed and coupled through a manual transmission to an electric swining field dynamometer providing both load absorbing and motoring functions.

In addition to normal apparatus for the measurement of engine revolutions, power and fuel consumption, the following instrumentation was employed:

1. Pressure indication to enable start of chamber pressure rise to be determined.
2. Injector needle lift indicator to give dynamic injection timings.
3. Bosch smokemeter for exhaust smoke density measurements.
4. Ricardo portable emissions equipment as described earlier (see section 3).
5. Ricardo air meter for the determination of volumetric efficiency and air flows.
6. Fuel pump rack position transducer to verify the earlier results obtained with the linkage transducer.

The engine was installed without fan or air conditioning compressor and the vehicle exhaust system for the naturally aspirated or turbocharged version was used as appropriate.

7.3 Test Procedure - Task 4

Initial tests were carried out in naturally aspirated build with the turbocharger removed and the original inlet and exhaust manifolds refitted.

In order to obtain complete calibration of the engine, load range performance was obtained at the following speeds: 15, 25, 35, 45, 55 and 65 rev/s with readings taken at bmep intervals of 1 bar from minimum load to maximum load. With these readings every mode of the vehicle drive cycle would be covered at steady state conditions.

Parameters of performance graphically recorded for each load and speed were as follows: brake specific fuel consumption, exhaust smoke density (by Bosch units), fuel quantity, exhaust temperature, dynamic injection timing, start of pressure rise, HC emissions, NO emissions and CO emissions. In addition normal running conditions such as water temperature, oil temperature etc. were monitored. Also at each load and speed the air flow to the engine was recorded and the figures used to compute brake specific emissions, air fuel ratios and volumetric efficiencies.

Replicate test results were obtained of all the above data to ensure repeatability of the engine. These tests took the form of check points taken at the same time or shortly after the main tests. The results of these check tests are shown on the performance curves so that the degree of repeatability can be seen.

The whole of the above test procedure was carried out with both N/A and T/C versions of the engine with additional data from the T/C engine recording the turbocharger performance.

Before each of the above test series a full load power curve was obtained as a check on the engine performance, and for each build of the engine motoring figures were obtained to provide emissions data under overrun conditions, as well as friction levels.

7.4 Test Results - Task 4

As a preliminary to the full calibration, tests were first conducted to assess the relationship between the accelerator linkage position transducer used in Task 3, and the linear transducer coupled to the injection pump rack which it was now possible to employ on the test bed. The output from the two transducers was simultaneously recorded by a pen recorder and comparisons of the two traces made under various conditions of load and speed. The results showed both transducers to give similar patterns of movement. With slight deviations at light load low speed and at idle when the injection pump governor was in a position to override the accelerator linkage. These deviations were not considered to influence the conclusions of the critical modes tests of Task 3.

The performance calibration was carried out first by obtaining a full load power check under naturally aspirated conditions followed by load range loops with replicate check points. Figure 14 shows the full load N/A performance and Figures 15-33 show N/A load range loops of engine performance, dynamic timings, exhaust emissions and friction with Figures 34-59 showing similar data for the T/C version of the engine.

From these data brake specific emissions were computed and these are shown on Figures 60-72 as composite maps and include similar data for fuel consumption and exhaust smoke density for both N/A and T/C versions of the engine. Additional data is also shown for the boost performance of the T/C engine in the form of a composite map.

Following the engine calibration recorded above, tests were carried out with the turbocharged version to establish the effect on gaseous emissions and performance of retard of injection timing. The results of these investigations are shown in Figures 73-90. It was intended that retard of injection timing would be used in conjunction with EGR to provide a more extensive NOx reduction. This information would also be of use in providing the data necessary for the re-scheduling of the automatic injection timing system for further improved control of emissions.

7.5 Discussion of Results - Task 4

The full load power curve for the naturally aspirated engine shown on Figure 14 indicates that the engine performance of 57 kW at 65 rev/s was up to the manufacturers specification. Under these full load conditions the exhaust smoke measured 3-4 Bosch units equivalent to 5-8% opacity (Reference 2).

The load range performance and emissions curves shown in Figures 15-32 indicates a typical response for this type of engine having increasing NO concentration with load. HC levels remained fairly constant over the load range as did the smoke level at about 3 Bosch units.

For the turbocharged version of the engine Figure 34 shows the full load power curve with the N/A performance also shown for comparison. It can be seen that a small fall off in maximum power has occurred corresponding with the slight drop in vehicle acceleration indicated in the results of Task 2. The inferior fuel consumption indicated from the Highway Fuel Economy Tests in Task 2 is not apparent under these full load conditions, but examination of the load range performance curves for the T/C version of the vehicle shown in Figures 35-58, reveals a 6-7% inferior specific fuel consumption over the naturally aspirated version of the engine at higher speeds.

Emissions results for the turbocharged engine show the levels of NO to be higher and the levels of HC to be slightly lower than those measured on the N/A engine. These results are compatable with the emissions results obtained from the T/C version of the vehicle in Task 2.

For all these tests the replicate sets of results are indicated and can be seen to give only small variations from the first tests. These are considered to be good replications.

Friction levels of the engine in N/A and T/C builds are shown in Figures 33 and 59 respectively. Most important are the emissions of unburned HC which remain under overrun conditions. These levels will have to be taken into consideration when computing the test bed steady state results to simulated vehicle results for future tasks.

The brake specific curves shown in Figures 60-72 show typical responses for small indirect injection diesel engines. In each case these curves were derived from the first test as more complete data existed from these results. From these composite maps any particular emission or performance parameter can be extracted at any load or speed of the engine.

The effect of retard of injection timing is shown in Figures 73 to 90. The response of the engine performance is typical of small indirect engines giving inferior specific fuel consumption and power but improved exhaust smoke opacity as the injection timing is retarded. The timing was retarded in 3 stages of 3 crank degrees. At 6^{o} retardation little or no change was made to gaseous emissions but at 9^{o} retard considerable increase in HC can be seen to have occurred, particularly at light load, with an overall reduction in NO emissions. These results show that to gain any real advantage in NO emissions at least 6° retard will have to be made in conjunction with EGR in future tasks. The possible development of an automatic injection timing system to provide modulations with both speed and load, with the object of reducing NO emissions without detriment to HC emissions or engine performance, could be a future line of investigation.

7.6 Conclusions - Task 4

The completion of these tests has provided a comprehensive baseline performance of the Mercedes OM617 engine in both N/A and T/C builds. The gaseous emissions have been shown to be representative of those for this type of engine. Response of the engine performance and gaseous emissions to retard of injection timing has also been normal.

Of particular importance are the composite maps of brake specific fuel consumption and emissions which will be directly comparable with those obtained with the modulated EGR systems in future tasks.

8. TASK 5 - DESIGN, FABRICATION AND APPLICATION OF THE VARIABLE EGR SYSTEM

8.1 Introduction - Task 5

For the most effective control over the recirculation of the exhaust gas to the intake of the engine a system had to be devised that could initially be controlled manually for test bed calibration with subsequent automatic operation.

Several alternative valve arrangements were considered including existing EGR valves as used on gasoline engines but it was envisaged that a much greater quantity of EGR would be required than these valves could deliver, especially considering that virtually no inlet manifold depression would exist to assist in the EGR flow.

It was decided therefore to design and manufacture a simple system having two manually controlled butterfly valves, one to control the exhaust gas recirculation flow, and one to produce an artificial intake depression for use when the EGR flow was insufficient with the first valve fully open. Each valve was of about 2" diameter and had the advantage of simple operation and construction. Figure 91 shows one of the valves complete with manual control.

For the method of supplying the EGR to the engine intake three alternative arrangements were considered: a) supplying the EGR through the compressor intake from the relatively low pressure exhaust system, b) supplying EGR direct into the inlet manifold from the high pressure exhaust gas upstream of the turbocharger turbine and c) extracting EGR from the high pressure exhaust gas as in (b) above but supplying it into the turbocharger compressor inlet as in (a). These alternative methods are illustrated in Figure 92 (a, b and c). Of the three alternatives a) had the advantage of lower EGR temperature and good mixing of the air and exhaust gas in the turbocharger compressor, b) had disadvantages of high temperatures and poorer mixing and c) had high temperature disadvantages but advantages of good mixing and possible smaller pipe and valve due to the higher exhaust pressure.

The first of these methods was the one chosen for these tests and the installation of the EGR valves on the engine is shown in Figure 93a with Figure 93b showing the test bed installation. The EGR was tapped from the main exhaust at a position approximately 6 feet from the exhaust valves of the engine to provide some measure of cooling to the gas.

8.2 Test Procedure - Task 5

Calibration of the engine with EGR was carried out to the same procedure as that for the earlier tests in Task 4 above. Load range curves were taken at the same speeds as previously but this time with the EGR the flow rate being fixed at various levels at each speed.

The percentage of exhaust gas in the intake of a diesel engine can be established by proportioning the CO_2 readings in the recirculating gas and the inlet manifold air/EGR mixture or by the drop in intake air flow measured in relation to the zero EGR air flow. For the purposes of these tests the reduction of air flow was employed as the measurement of the EGR as it was more convenient to maintain a constant percentage flow rate throughout the load range of the engine by this method. The EGR rate by CO_2 ratio was also noted for each reading and indicated somewhat less EGR flow than for the air flow method.

The actual percentage rate of EGR was not important for these particular tests as the only requirement was to be able to reproduce the conditions of the test bed on the vehicle in future tests.

8.3 Results - Task 5

The response of the engine to EGR quantity over the load range at the six test speeds and at idle is shown in Figures 94-106. These curves indicate the changes in emissions and performance as the EGR rate was increased by steps of 10% (by air flow reduction). A constant EGR level was maintained over the load range by fine adjustment of the control valves with the butterfly valve controlling the intake depression being maintained fully open until maximum flow was attained on the exhaust gas control valve.

EGR levels of up to 80% (by air flow reduction) were achieved at some load and speed combinations but in practice these high levels were not acceptable at other than light load at most speeds due to the onset of misfire. Also, as the level of EGR was increased the maximum acceptable load of the engine was limited by one or more of the following factors:

a) excessively black exhaust smoke
b) an exhaust CO level of over .2% (indicative of black smoke)
c) inlet manifold temperature limited to 220°C approximately
d) turbine entry temperature limited to 750°C approximately.

At any one of these limitations the amount of exhaust gas recirculation would be beyond the amount possible in any practical system because of other factors such as loss of power and greatly increased specific fuel consumption.

8.4 Analysis of Results - Task 5

From the results shown in Figures 94-106 it can be seen that the response of the engine follows a reasonably stable relationship with EGR percentage. However although it is shown that at high load the NO level reduces dramatically with increasing EGR this effect is clouded by the severe reduction in allowable load at high EGR levels. Similarly the increase in HC and CO levels with increasing EGR would be greater if the load level of the engine were not restricted, as would be the increase in specific fuel consumption and exhaust smoke. This response can be seen to be common for all engine speeds.

As load is reduced the response of the engine to increasing EGR becomes less until the EGR percentage reaches 40% when the HC emissions begin to increase.

At higher levels of EGR the CO also increases rapidly but exhaust smoke remains unchanged at light load. Reductions in NO are also less dramatic at light load as EGR is increased but the effect of EGR on vehicle emissions would be greater as the reduced air consumption of the engine, due to the induction of EGR, would increase the dilution factor of the CVS analytical apparatus.

Computer Simulation Program

In order to relate these results to vehicle emissions a CVS simulation computer program was used which could accommodate a modulation of EGR based on the engine load and speed requirements of the 1975 FTP drive cycle. This was a modification of the Ricardo CVS simulation program used to predict vehicle emissions from steady state test bed results.

To assess the validity of the computer program, data from the zero EGR steady state tests were used and simulated vehicle results obtained for comparison with the actual vehicle results. These comparisons were initially unsatisfactory, possibly due to the use of input data from the engine with a manual transmission being compared with the automatic transmission actually used on the vehicle. To overcome this problem the engine revolutions/time data which were obtained from the vehicle during the critical modes section of the vehicle tests (Task 3), together with injection pump (engine load) data, were employed to give a precise mapping of engine performance at all parts of the driving schedule, thus obviating the necessity of modelling the transmission system.

The results of these computations gave emissions levels higher than those of the original vehicle as can be seen below:-

	HC gpm	NOx gpm	CO gpm	Fuel Cons. mpg
Original vehicle T/C zero EGR	.14	1.75	.94	23.8
Computed zero EGR	.16	2.58	1.29	21.2
% increase	14.3	47.4	37.2	11.3

These figures were in closer agreement than for the original computation although some improvement in NOx correlation might be made. A possible source of error is that the computer model made no allowance for the moisture content of the NO emission thus producing a higher result. Similarly it should be noted that the 1975 FTP drive cycle consists entirely of transient modes whereas the computer model relies on the abstraction of data from engine steady state tests results. In addition the FTP cycle differentiates between cold and hot results. No such modifications of steady state data is possible. It was considered, however, that from the existing program sufficient data could be obtained to enable trends of vehicle emissions to be established from the test bed results with varying amounts of EGR.

Simulated EGR Modulation

In order to achieve simulated vehicle emissions from the steady state EGR response curves it was necessary to produce matrices of all the test parameters at the EGR level applicable to the particular modulation chosen.

To simplify the process it was necessary to redraw the performance and emissions curves on to an EGR base at 1 bar load intervals. Examples of these are shown in Figures 107 and 108 for 45 rev/s. From these and other curves any intermediate level of EGR could be chosen at any speed and the particular parameter recorded in a matrix at 1 bar load intervals.

As the HC emission of the vehicle was low (about one third of the maximum limit allowed) initially an EGR level was arbitrarily chosen that produced a three times increase in HC level on the test bed. For example on the curves shown in Figure 108 at zero bmep and zero EGR, the HC level reads 45 ppm. Three times 45 = 135 and at zero bmep 135 ppm is reached at 53% EGR. Similarly at 3 bar the HC level is 30 ppm at zero EGR and at 3 x this level the EGR percentage is 43.

Using this procedure a complete map of EGR levels was drawn up for each load and speed but modified to give zero EGR at full load in order to prevent any loss of full load performance. The EGR map produced by this method is shown on Figure 109 and using these data the modified levels of the other parameters were identified and prepared for computation. The following parameters were recorded at each of the six speeds at 1 bar load steps; EGR %, NO ppm, HC ppm CO%, air meter reading, fuelling mm^3/injection and pump rack position.

The latter three parameters were obtained from separate sets of curves and in addition to the above, a bmep/rack position matrix had to be produced to provide modified load data for the simulated FTP cycle to allow for the fall off in mid load power for a given fuelling level caused by the application of EGR. Similarly an allowance was made for the changes in idle emission levels with EGR. For overrun conditions the emissions levels obtained during the motoring tests without EGR were used.

The result of the computation from the EGR modulation of Figure 109 (designated Mod. 1) is shown below with the simulated zero EGR results for comparison.

	HC gpm	NOx gpm	CO gpm	Fuel mpg
Zero EGR	.16	2.58	1.29	21.1
Mod. 1	.2	.57	2.33	20.9

The figures show that for the particular EGR modulation shown in Figure 109 the predicted NOx emission would be reduced to one fifth of the zero EGR condition with the HC and CO emissions almost doubled. These results were only indications of likely trends produced by the EGR modulation and were not indicative of actual vehicle results which would only be apparent if that particular EGR map could be applied to the vehicle in future tests.

Having established a technique for the simulation of vehicle emissions, which could be applied to any modulation of EGR, it was necessary to attempt to apply the above modulation to the Mercedes OM617 engine. To this end the EGR map, Mod. 1, was transferred point by point to a series of curves relating fuel pump linkage position (i.e. engine load) to EGR valve position at each of the six engine speeds. These curves are shown on Figure 110 and it can be seen that the relationship between valve position and fuel pump linkage position was reasonably close at 25, 35, 45 and 55 rev/s but was different at the extreme speeds of 15 and 65 rev/s. This factor is indicative that in order to exactly reproduce this particular EGR modulation on the engine, some speed sensitive device would be necessary to modify any direct EGR valve to fuel pump linkage at extremes of the speed range.

In order to investigate the effects of employing only direct connection between the EGR valve and injection pump linkage positions two additional curves based on those of Figure 110 were produced each showing all six speeds as a common relationship. These curves are shown on Figure 111 and were subsequently transferred to full EGR modulation maps on Figures 112 and 113 to be designated Mod. 2 and Mod. 3 respectively.

At the same time it was clear that for Mod. 1 shown earlier (Figure 109), the level of EGR indicated at zero load (and at idle) of 60 to 70% would be impracticable due to excessive white smoke and difficulty in controlling the engine. Therefore it was decided to recompute the emissions results using a maximum EGR level of 50%. The result of these changes raised the NOx figures slightly and surprisingly also increased the HC and CO predicted levels.

The results are tabulated below with those of the original Mod. 1 and for Mods. 2, 3 and 4. The zero EGR computed figures are also shown.

	HC gpm	NOx gpm	CO gpm	Fuel mpg
Zero EGR	.16	2.58	1.29	21.1
Mod. 1	.2	.57	2.33	20.9
Mod. 1 (50% Max. EGR)	.22	.61	2.46	20.94
Mod. 2	.17	1.31	1.6	20.9
Mod. 3	.21	.76	2.22	20.37
Mod. 4 (Fixed Orifice)	.14	1.2	1.6	21.0

Mod. 4 shown in the above table was for a calculated fixed orifice equivalent to producing a 15% reduction in full load power to comply with one of the objectives in the original programme. This fixed orifice was equal to an EGR rate of 10% at full speed increasing to approximately 20% at low speed with no variation with load. The NOx emission at 1.2 gpm represents 46% of the zero EGR level.

The NOx results for Mod. 2 and Mod. 3 were reduced to 50% and 30% of the zero EGR levels respectively. Although both modulations were derived from a theoretical direct linkage between valve and pump linkage the deviations shown on Figure 111 at mid load caused considerable changes in the rate of application of EGR which can be seen by comparison between the Mod. 2 and Mod. 3 maps on Figures 112 and 113. The effects of these differences are shown in the results table above with the Mod. 3 figures being comparable with those of the reduced EGR Mod. 1 figures.

EGR Valve Configurations

From an analysis of all the above computer results it was evident that the existing arrangement of EGR control on the engine employing two butterfly valves was not ideal. Additionally the butterfly valve controlling the EGR flow operated at high temperature, and in consequence suffered considerably from distortion problems which caused difficulty in adjustment and in fully closing the valve for zero EGR conditions. In addition the test bed results indicated that more than sufficient EGR for practical results could be obtained without the use of the depression inducing butterfly valve in the engine intake system. Also from the above computer simulations it was evident that an EGR level directly controlled by accelerator linkage could be satisfactory although with a non-linear load relationship.

At about this time consideration was given to an alternative method of modulating the EGR flow consisting of a number of vacuum operated valves capable of being switched in in sequence, thus giving a stepped function according to demand. This was persued in a practical manner by regulating the EGR by an orifice plate consisting in the first place of one ⅜" dia. hole then two holes, then three and so on. The orifice area of each hole was considered to be about equal to that obtaining with a gasoline type EGR valve. Consideration of the EGR flow showed that seven valves of this type would be required to achieve 55% EGR. Whilst the control of such multiple valves held some attraction in so far as a very quick response time and simple operation could be achieved, nevertheless space considerations precluded such a multiple array. In view of these findings this system was not developed any further and a new valve having a poppet or obturator type valve head giving a continuously variable EGR function was developed.

Experiments to operate such a valve by suction using the vehicle's vacuum system were carried out. Such a system would have the advantage of simplicity, being similar to that used on many gasoline engines, but would of necessity have to be larger because of the much greater quantities of EGR involved. These tests showed however that the response time of a vacuum cell was rather slow in comparison with a direct mechanical control which would give an instant response and this system was abandoned in favour of the mechnical linkage.

The new valve was therefore designed and constructed together with an eccentric cam operating mechanism connected by a flexible cable to the injection pump control linkage. The design of this valve was such that the valve head could be assembled to open or close against exhaust gas pressure as shown in Figure 114.

By adjustment of the position of the cam relative to accelerator position and by change of profile of the valve head a very extended range of EGR modulation with load could be achieved. In addition, with the valve closing by gas pressure, the rate of closure could be controlled by setting a backlash adjustment on the cam which, because the exhaust pressure changed with speed, would give a measure of speed modulation of the EGR. Figures 115 (a) and (b) show the installation of the new valve on the engine and the prototype operating mechanism.

Figure 116 shows the first EGR modulation map obtained from the engine with the arrangement shown in Figures 114 and 115 with the valve set to lift 20 mm from its seat at 0% accelerator link travel (idle conditions) and zero lift at 100% accelerator link travel. This EGR modulation (designated Mod. A) is comparable with Mod. 2 or 3 shown in Figures 112 and 113 and the simulated vehicle emissions results for these Mods. are shown below:-

	HC gpm	NOx gpm	CO gpm	Fuel mpg
Zero EGR	.16	2.58	1.29	21.1
Mod. 2	.17	1.31	1.6	20.9
Mod. 3	.21	0.76	2.22	20.37
Mod. A	.145	1.13	1.57	21.26

It can be seen that the Mod. A result falls between Mods. 2 and 3 in respect of NOx emission but is improved in respect of HC, CO and fuel consumption.

The establishment of this operational EGR system concluded actual test work under Task 5 of the programme. Further work aimed at achieving the targets designated in the objectives is the subject of Task 6.

8.5 Noise and Durability

Subjective noise observations were made during the test bed calibration of the engine's response to EGR. It was shown that at low to moderate levels of EGR combustion noise was reduced and the low rate of pressure rise observed confirmed this. However at high levels of EGR combustion noise could be very sharp and erratic especially under cold start conditions. It was also noted that the intake silencing of the engine became very much impared with any level of EGR as the unsilenced exhaust became directly connected to the engine inlet system.

Although durability was not an integral part of the test programme the effects on engine performance etc. of inducing large quantities of exhaust gas were noted.

During the tests reported above, a gradual fall in boost pressure was observed and to assess this the EGR valve was removed and the supply pipe blanked off, to eliminate the chance of exhaust gas leakage into the intake system, and a full load power curve over the speed range of the engine obtained. This was shown to give a 40% lower boost pressure at 65 rev/s with 6.5% lower power. At lower speeds the boost pressure, power and bmep were all correspondingly lower than for the original power curve. It was suspected that the prolonged running with relatively high levels of EGR may have affected the turbocharger and to investigate this it was removed for inspection. On dismantling, the turbocharger compressor was found to be lightly coated with an oily, sooty deposit on the vanes and surface of the compressor housing. This was easily removed. The wastegate valve, spring and diaphragm were lightly coated with soot but were apparently in good working order, although all components had obviously been overheated in some degree. In order to increase the boost pressure to its original level, shims were placed under the wastegate spring to an amount calculated from the rate of the spring and the increase in pressure required. The turbocharger was reassembled without further change. The engine had run for approximately 45 hours at varying levels of EGR up to this time.

Before re-installing the turbocharger on the engine the inlet manifold was removed and the condition of the inlet ports and valves examined in situ. The ports and rear of the valve heads were slightly covered with the same oily soot deposit as on the turbocharger compressor. This was also present in the inlet manifold but was not considered to be detrimental to the engine performance. The turbocharger was therefore refitted to the engine without further change. A further full load power curve was obtained from the engine which resulted in a complete restoration of performance to that of the original test. The boost pressure was shown to have risen to 10% above that of the original test due to the combined effects of cleaning the turbocharger compressor and increasing the wastegate spring pressure, and it was decided that this would be acceptable for future tests as the level of boost was in any case relatively low. Figure 117 shows the repeated power curves with the original test shown for comparison.

Further evidence of EGR causing deposits to build up were shown on the EGR butterfly valve used for the majority of the tests and of near blockage of the sample pipe from the inlet manifold to the CO_2 analyser.

The effects of prolonged running with EGR were not established from these tests but would be likely to cause detriment to the performance of the engine.

8.6 Conclusions - Task 5

The results detailed above show a complete response of the Mercedes OM617 engine over the load and speed range covered by the 1975 FTP with a wide range of EGR flow rates. The main calibration was carried out using a butterfly valve to control the EGR and an additional identical valve to provide an artificially high induction depression to assist in the EGR flow when the main valve was fully open.

To quantify the effects of EGR on vehicle emissions it was necessary to extract theoretical modulations of EGR from the steady state test bed data and simulate by computer the 1975 FTP drive cycle. This was successfully carried out although exact correlation with vehicle results without EGR was not achieved nor perhaps could properly be expected. The simulations however were sufficiently accurate to enable trends to be established for comparison between zero EGR and various levels of modulated EGR. These modulations were derived arbitrarily from the test bed results and provided a basis for the establishment of a mechanical linkage to operate the EGR control valve directly from the engine fuel pump linkage.

The test bed response of the engine to EGR suggested that the depression inducing butterfly valve was unnecessary as sufficient EGR was available without its use. It was considered therefore that a single poppet type valve would be more appropriate and this was duly manufactured. This valve was controlled by flexible cable, through an eccentric cam, from the injection pump linkage thus having response to engine load. An option of having a degree of speed modulation was provided by allowing gas pressure to modify the valve operation at certain conditions.

First results with this system showed that good control of the EGR was possible and a 50% reduction in NOx emission was achieved. The arrangement of operation and valve design gave a wide range of possible variations for covering the target figures for the objectives of the programme to be achieved in in Task 6.

9. TASK 6 - KEY MODE TESTS WITH COMBINED MODULATED EGR AND OPTIMISED INJECTION TIMING

9.1 Introduction - Task 6

In consideration of this task it was clear from previous results that tests at key modes implies all parts of the FTP cycle. Therefore the EGR modulation exercise carried out in Task 5 is also applicable to Task 6.

The objectives of the programme, to be achieved on the test bed engine in Task 6 and repeated on the 300D vehicle in Task 7, were stated in section 2.6. It was considered however that these constraints required interpretation in greater detail and the objectives are therefore re-stated below with the slight modifications underlined.

1. Use EGR to obtain reduced NOx with minimum trade-offs to power, smoke and fuel consumption with increase in HC and CO limited to, say, 20% above the zero EGR version naturally aspirated.

2. Modulation of EGR to give minimum NOx emissions with no more than .41 gpm HC but retain the performance such as to allow the vehicle to be driveable.

3. Employ the level of EGR required to minimise NOx but retain not less than 85% of the N/A engine performance at each speed.

4. The level of EGR estimated to achieve 0.3 - 0.4 gpm NOx if 2 and 3 are estimated to result in lower than 0.4 gpm NOx.

5. The minimum level of EGR estimated to achieve 1.0 gpm NOx with minimum trade-off in other areas.

Although it was possible that two or more of the above targets would be achieved with one EGR condition, the actual affect on the vehicle performance of the application of EGR was not known until the system was applied to the vehicle in Task 7.

9.2 Test Procedure - Task 6

The methods of obtaining the simulated vehicle emissions noted in the previous task were applied to these tests. It was necessary to obtain EGR modulation maps from the engine (such as Mod. A shown in Figure 116 in Task 5) with differing builds of the EGR valve and operating mechanism. These new modulations were computed in the same way to provide predictions of vehicle emissions. Using the zero EGR prediction in Task 5 as a base, seven variations in EGR level, including Mod. A from Task 5, were assessed and estimated to cover the range of constraints documented above in section 9.1.

For each build of the EGR system, a complete map of EGR percentage (by air flow reduction) was obtained over the load and speed range of the engine.

From this map the levels of each of the emissions and performance parameters were abstracted using the previous EGR response curves. These data were applied to the computer program as previously to obtain the simulated vehicle emissions.

Further computation was applied to the results of each of the seven EGR builds to obtain brake specific emissions maps which are detailed in section 9.3 following.

9.3 Results - Task 6

The seven variations in EGR modulation were produced by combinations of valve seat diameter, valve head profile, valve lift and changes from upward to downward closing valves. These builds were designated Mod. A to Mod. G and were assembled from the parts detailed below:-

Valve Head No.	Details
1	45° seat - not used.
2	Profiled 10° for 6 mm Lift then 45°.
2a	As for 2 but reduced clearance.
3	As for 2a but increased dia. and raised rim.
4	Profiled 10° for 12 mm lift then as 3.
Valve Seat No.	
1	1.25 dia. for use with heads 1, 2 and 2a.
2	1.35 dia. for use with heads 3 and 4.
Actuator	
1	Eccentric cam operated, upward closing only.
2	High lift lever, downward closing.
3	Low lift lever, downward closing.
Operation	
U	Upward closing - can also be gas pressure modulated by using backlash on cam.
D	Downward closing.

The specific arrangment of the EGR valve for each of the modulations was as follows:-

	Valve Head	Valve Head	Actuator	Operation	Valve Lift/Link Position Settings
Mod. A (From Task 5)	2	1	1	U	20 mm at 0% 0 mm at 100%
Mod. B	3	2	2	D	44 mm at 0% 0 mm at 100%
Mod. C	4	2	2	D	45.5 mm at 0% 0 mm at 100%
Mod. D	4	2	3	D	17 mm at 0% 0 mm at 100%
Mod. E	4	2	3	D	18.5 mm at 0% 1.5 mm at 100%

	Valve Head	Valve Head	Actuator	Operation	Valve Lift/Link Position Settings
Mod. F	2a	1	1	U	23 mm at 0% 0 mm at 100%
Mod. G	2a	1	1	U	25.5 mm at 0% 1.5 mm at 100% + 2 mm backlash

It should be noted from the modulation shown earlier on Figure 116 (Mod. A) the maximum EGR rate was 40%. For subsequent builds of the valve using downward closing arrangements, the valve head was designed with an extended upper rim which obstructed the air intake of the engine thus assisting in the induction of a greater quantity of exhaust gas under light load (high valve lift) conditions. It will be seen that for Mods. B and C 60% EGR was achieved at light load. (See Figures 123 and 129).

The 2 mm backlash referred to in Mods. F and G in the above table are the static valve lift which would be subtracted from the dynamic valve lift at high loads and speeds to reduce the EGR under these conditions. In practice the gas pressure was set to reduce the valve lift at full load above 45 rev/s. At lighter loads the change over would occur at higher speeds.

The EGR maps obtained from these modulations were plotted and emissions data extracted from the earlier EGR response curves for application to the computer program. In addition the results were computed to produce brake specific emissions and performance data from which composite maps were constructed. These maps are shown in the following Figures:

For Mod. A - EGR map Figure 116 (shown in Task 5) brake specific emissions, Figures 118-120, brake specific fuel consumption, Figure 121, exhaust smoke opacity (Bosch units) Figure 122.

Mod. B - EGR map Figure 123, emission maps, Figures 124, 125 and 126, specific fuel consumption maps, Figure 127, exhaust smoke, Figure 128.

Mod. C - Figures 129-134
Mod. D - Figures 135-140
Mod. E - Figures 141-146
Mod. F - Figures 147-152
Mod. G - Figures 153-158.

The simulated vehicle results for each of these EGR modulations are shown in the table below with the zero EGR prediction and the actual vehicle result shown for comparison.

Mod.	HC gpm	NOx gpm	CO gpm	Fuel mpg
A (Task 5)	.145	1.13	1.57	21.26
B	.42	.689	8.535	20.97
C	.269	.589	4.168	20.84
D	.147	1.131	1.607	21.11
E	.179	.714	2.2	21.05
F	.163	.879	1.724	20.9

Mod.	HC gpm	NOx gpm	CO gpm	Fuel mpg
G	.23	.647	2.896	21.12
Zero EGR	.16	2.58	1.29	21.1
Actual Vehicle Tests	.14	1.75	.94	23.8

9.4 Discussion of Results - Task 6

It was considered from the results shown above that the objectives indicated in section 9.1 could be covered by these EGR modulations. Until actual vehicle tests were carried out however this remained uncertain. The EGR valve build most effective in reducing NOx was that for Mod. C, where a reduction of 77% in the zero EGR simulated result was achieved. This was however at the expense of excessive CO production. Figure 134 shows the smoke levels recorded and it can be seen that up to 8 Bosch units were reached at low speed.

Other results shown in the above table gave similar low NOx predictions. Mods. B and G produce NOx reductions of about 75% with, for Mod. B, much higher CO levels, and for Mod. G much lower CO levels. Inspection of the respective EGR modulation maps shown in Figures 123 and 153 show that the EGR level for the latter was lower at light load but at maximum load some EGR was retained giving a lower maximum bmep level. The brake specific CO maps for these conditions (Figures 126 and 156) show the changed distribution and values which resulted in these figures.

Also of interest in the above table are comparisons between Mod. D and E results and between Mod. F and G results. For these cases, E and G both retained some EGR at full load varying between 10 and 15% for Mod. E and 2 to 10% for Mod. G. In each case the retention of some EGR at high load resulted in an extra 25-30% reduction in NOx but with similar increases in HC and CO emissions. Reductions in maximum power also occurred within the 85% level required for constraint No. 3 in section 9.1.

It should be noted that the calculated fuel consumptions in the above table vary only over a small range despite the wide range of emissions results predicted.

The fuel consumption was calculated from the quantity of fuel used and for a given load was increased according to the application of EGR. Although this may show considerable differences in specific fuel consumptions at the high levels of EGR on the engine steady state curves the vehicle fuel consumption is of course dependent on the load and time factors as determined by the computer program. These fuel consumption results were varified on the vehicle in Task 7.

As predicted emissions levels for the zero EGR condition on the vehicle were higher than the actual vehicle tests it was assumed that the modulations shown above would produce a lower result when applied to the actual vehicle. In the event this proved the case for NOx but not for HC emissions. This is fully detailed under Task 7.

In addition to the work described above, an objective of Task 6 was to test with optimised injection timing. These tests were not carried out at that time however, as for these EGR modulations no emissions observations were required, the data being extracted from the earlier EGR calibration. At the time the only injection timing data available was for the zero EGR condition. It was considered therefore that the effect of injection timing retard could be achieved more effectively on the vehicle during Task 7.

It should be noted that during the above tests on the engine, misfire, accompanied by white smoke, and excessive combustion noise occurred when cold, under some of the higher EGR conditions. These effects could be expected to be more severe on the vehicle under cold start conditions. Also it was noted that excessive induction noise was evident under all but zero EGR conditions as the EGR valve effectively opened the exhaust to atmosphere, thus by-passing the silencing system. These effects had previously been noted during the EGR calibration.

9.5 Conclusions - Task 6

The objectives of Task 6, to attain the EGR modulations estimated to meet the constraints laid down, were assumed to have been achieved. The seven EGR modulations carried out cover a range of NOx emissions which when simulated into vehicle output and compared to the zero EGR simulation, produced NOx levels which would match each constraint.

The effect of retard of injection timing was not investigated at this time but would be carried out during Task 7 on the vehicle. It was noted that under some conditions white smoke occurred; this would be accentuated under retarded injection conditions.

10. TASK 7 - TESTING AND ASSESSMENT OF EGR SYSTEM INSTALLED IN THE VEHICLE

10.1 Introduction - Task 7

The engine, complete with EGR system and automatic transmission was re-installed into the Mercedes 300D vehicle.

Before the re-installation was carried out the turbocharger, inlet manifold and EGR valve were inspected for signs of carbon deposit build up such as those previously reported in Task 5, section 8.5 - see paragraph 10.2 immediately following.

After reassembly the vehicle was calibrated using the same test procedure as for Tasks 1 and 2 using a range of EGR modulation developed during Task 6.

10.2 Durability

The removal of the turbocharger and inlet manifold revealed considerable deposits of black carbon. In particular on parts of the scroll of the turbocharger compressor housing and a section of the inlet manifold adjacent to the compressor outlet where quiescent conditions existed. Black oily deposit was also present on the compressor rotor and sides of the inlet manifold and inlet ports. There was some build up of deposit on the back of the inlet valves, more evident on 1 and 2 ports adjacent to the intake, also the gas sample point from the inlet manifold was almost completely blocked. At this time the engine had completed 96 hours with mixed EGR running, 51 hours since the turbocharger compressor was last cleaned. The deposits described above were not considered to have caused any substantial change in performance at this stage, but further running would increase the likelihood of adverse affects on performance. Before reassembly the turbocharger and inlet manifold were cleaned.

The EGR valve was similarly inspected and found to be reasonably clean. The design of the valve and seat were such as to be self cleaning (by vibration) and no deposits were to be seen on these parts.

10.3 EGR System Installation

The installation of the EGR system in the vehicle was accomplished without difficulty but certain modifications had to be carried to the system as used on the test bed. These changes were mainly of a minor nature the most important of which was the re-construction of the EGR pipe to avoid contact with other parts of the vehicle installation. This pipe also had to be shortened on the vehicle being tapped into the main exhaust pipe at approximately 4 feet from the cylinder head compared with 6 feet on the test bed. This may raise the temperature of the EGR at the valve but the effect would be offset by the presence of cooling air resulting from the motion of the vehicle. In addition the more transient nature of vehicle operation would prevent such high temperatures as were possible under test bed steady state conditions.

Other changes to the EGR valve installations involved small differences to the operating mechanism, none of which altered the characteristics of the system.

10.4 Test Procedure - Task 7

Assessment of the Mercedes 300D vehicle with EGR was carried out in the same way as for Tasks 1 and 2 which was as follows:

1. 1975 FTP tests for gaseous emissions
2. EPA HFET
3. Exhaust smoke obscuration tests
4. Particulate emissions measurement
5. Drive-by noise measurements
6. Vehicle performance assessments.

Replicate tests were made, where possible, the test series being repeated with EGR levels and injection timings set for each of the constraints set out earlier. To establish the exact EGR valve build to reach these constraints several additional tests were carried out with various modifications to the modulation system.

10.5 Results - Task 7

Initial runs with the vehicle were carried out with the EGR build last used on the test bed. This was Mod. G with a modulation of EGR as shown in Figure 153. The results of replicate tests for the 1975 FTP with this EGR modulation are shown below with the predicted computation shown for comparison.

	HC gpm	NOx gpm	CO gpm	Fuel mpg
EGR Mod. G vehicle (Mean of 2 runs)	.395	.528	2.408	19.47
EGR Mod. G Simulated	.23	.647	2.896	21.12

It can be seen that the NOx level was lower than predicted by the simulation program as suggested in Task 6, section 9.4. The HC emission was however higher than predicted. These results have shown that for the particular EGR modulation employed, constraint number 2 shown in section 9.1 for .41 gpm HC emissions, was achieved. This EGR modulation could also cover constraint 3 for reduction of maximum power.

The remaining tests shown in 10.4 above were carried out and the full list of results for EGR Mod. G is shown below with the original as received vehicle results shown for comparison.

	EGR Mod. G			As received
Emissions 1975 FTP	Test 1	Test 2	Mean	N/A
HC gpm	.383	.406	.395	.183
NOx gpm	.575	.48	.528	1.66
CO gpm	2.324	2.492	2.408	.94
Particulates gpm	1.11	-	-	.8

	EGR Mod. G			As received
Fuel Economy	Test 1	Test 2	Mean	N/A
CVS test mpg (US)	19.52	19.41	19.47	24.3
Highway test mpg (US)	24.94	-	-	29.95
Vehicle Performance				
Acceleration time sec.				
0-40 mph			10.6	9.6
0-60 mph			23.5	21.2
20-60 mph			20.1	18.7
Drive-by Noise (SAEJ986a)				
30 mph low gear dBA			*78.0	74.2

*This noise figure was artificially high due to contact between vehicle chassis and exhaust system. No retest figure available.

Exhaust Smoke

A smoke trace obtained over the FTP cycle showed slight increases over the original vehicle build. However a high peak of 100% opacity was recorded during the cold start compared with the original 20%. High speed cruise increased from 4 to 8%. Idle increased from 6% to 8-10%. Average high peaks on acceleration when hot were 60% compared with original vehicle test of 10%.

Observed smoke on road test was not excessive under any driving conditions although some smoke was visible at all times. Some misfire occurred during cold starting and at low speed cruise conditions.

It should be remembered that EGR Mod. G produced a loss of power at full load as some EGR was applied under these conditions.

To attempt to establish the minimum NOx emission possible the EGR valve build was modified to that required for Mod. C which produced the lowest NOx level during Task 6. To reduce the NOx level further the valve build was further modified to allow some EGR to be retained at full load as for Mod. G above.

The resulting EGR map from this modification cannot be known for certain but would not be changed unduly from that shown in Figure 129 apart from a loss of maximum bmep and modified full load EGR levels. This build of the EGR valve was designated Mod. C+ and the emissions results for the 1975 FTP are shown below:

	HC gpm	NOx gpm	CO gpm	Fuel mpg
EGR Mod. C+	.382	.471	2.379	19.95

These results did not produce the expected reduction in NOx but would also be applicable to constraints 2 and 3 as for EGR Mod. G shown above. Replicate tests were not carried out for this condition neither were the additional tests for vehicle assessment.

To further reduce the NOx emission, maintaining the same EGR valve modulation, the injection timing was retarded 7 crankshaft degrees. This figure was chosen as it was shown during the test bed calibration of Task 4 the 6° injection retard had little effect on emissions.

The results gave a very useful reduction in NOx and a further change to 4° retard was made. Both timing changes gave increased HC emissions as shown in the table of emissions results below:

	HC	NOx	CO	Fuel	gpm
EGR Mod. C+ 7° retard	4.974	.32	6.129	17.15	
EGR Mod. C+ 4° retard	1.053	.379	2.956	18.86	

These figures are means of replicate runs and show that below .4 gpm NOx could be achieved but with considerable increases in HC and CO emissions, (The HC being above the legislated limit for both conditions.)

With these high levels of EGR and 7° injection retard it was not considered advisable to carry out a HFET as the high speed nature of the test may have caused damage to the engine due to excessive temperatures of the exhaust gas and EGR system. Some performance and noise tests were conducted however. Full results are shown below.

Emissions 1975 FTP			Test 1	Test 2	Mean
	HC	gpm	4.885	5.062	4.974
EGR Mod. C+ 7°Retard	NOx	gpm	.322	.317	.32
	CO	gpm	6.299	5.959	6.129
	Particulates	gpm	.931		
	HC	gpm	.975	1.131	1.053
EGR Mod. C+ 4°Retard	NOx	gpm	.399	.359	.379
	CO	gpm	2.971	2.941	2.956
	Particulates	gpm	1.228		

Fuel Economy					
Mod. C+ 7°Retard	CVS	mpg	17.26	17.03	17.15
	HFET	mpg	-	-	-
4°Retard	CVS	mpg	18.57	19.15	18.86
	HFET	mpg	24.43	-	-

Vehicle Performance Acceleration time sec.		
	0-40 mph	11.6
Mod. C+ 7°Retard	0-60 mph	25.3
	20-60 mph	22.4
4°Retard	0-40 mph	11.0
	0-60 mph	25.3
	20-60 mph	22.4

These acceleration tests were conducted very briefly to keep vehicle running time to a minimum.

Drive-by Noise (SAEJ986a) 30 mph low gear - dBA	
7° retard	-
4° retard	76.2

Drive-by noise for the 7° retard condition was not possible due to continuously wet roads.

Exhaust Smoke

Smoke traces under 7° retard conditions gave reduced maximum levels when compared to the earlier tests with Mod. G. Maximum recorded 25% obscuration on cold start. 10% peaks were recorded under hot conditions with 4% at high speed and 6% at idle.

For 4° retard less than 10% obscuration was observed at cold start and the remaining levels were 20% maximum during hard accelerations with 3% at high speed and idle.

Observed smoke under driving conditions was very low for both builds but excessive white smoke for the 7° retarded condition was observed. With this EGR system and 7° or 4° timing retard the driving of the vehicle was very much impaired with misfire at steady speeds below 40 mph with hot or cold engine.

Constraint numbers 3 and 4 could be covered by these results which left numbers 1 and 5 outstanding. Both of these required a lesser quantity of EGR to be applied as follows:-

Constraint No. 1; the minimum EGR for minimum increase in HC and CO (increase limited to 20% see section 9.1).

Constraint No. 5; the level of EGR required to reduce the NOx to 1.0 gpm with minimum trade-off in other areas.

It was considered that these constraints could both be achieved with EGR Mod. D shown on Figure 135.

The build of valve to achieve Mod. D was identical to Mod. C+ above but was arranged with a reduced lift and the valve was set to close at full load to eliminate any performance loss. Standard injection timing was used. The emissions results produced by this build are shown below:

	HC gpm	NOx gpm	CO gpm	Fuel mpg
EGR Mod. D	.226	.961	1.563	20.08

These results fall within the requirements of constraint number 5, 1.0 gpm NOx.

To reduce the NOx level further and to reduce HC and CO emissions to achieve constraint number 1 the same EGR modulation was retained but the valve lift was restricted in two stages to 7 mm and 2 mm lift. The emissions results obtained are shown below:

EGR Mod. D	HC gpm	NOx gpm	CO gpm	Fuel mpg
7 mm lift	.245	1.004	1.391	20.17
2 mm lift	.171	1.52	1.329	20.28

The result of the first test (which was not replicated) shows little change on the Mod. D shown earlier. No further tests were carried out with this build. For the second test with 2 mm lift the HC level was reduced to below that of the original N/A vehicle result of .183 gpm. CO emissions however remained at about 40% higher than the original figure of .94 gpm. It was considered that no lower figure of CO could be obtained without complete removal of EGR as the maximum EGR level, for 2 mm lift of the valve, was only 10%. Therefore this was considered to be the EGR modulation to achieve constraint number 1 in section 9.1.

The complete test results for EGR modulations Mod. D and Mod. D- (2 mm lift) are shown in the following tables:

	Emissions 1975 FTP	Test 1	Test 2	Mean
	HC gpm	.245	.207	.226
EGR Mod. D	NOx gpm	1.02	.902	.961
	CO gpm	1.5	1.625	1.563
	Particulates gpm	1.59	-	-
	HC gpm	.201	.14	.171
EGR Mod. D- (2mm)	NOx gpm	1.429	1.613	1.52
	CO gpm	1.37	1.288	1.329
	Particulates gpm	.964	-	-

	Fuel Economy			
Mod. D	CVS mpg	Not available	20.08	20.08
	HFET mpg	25.78	-	-
EGR Mod. D- (2mm)	CVS mpg	20.4	20.16	20.28
	HFET mpg	25.87	-	-

Vehicle Performance Acceleration times sec.		Mean
	0-40 mph	10.2
Mod. D	0-60 mph	22.6
	20-60 mph	19.1
	0-40 mph	9.4
Mod. D- (2mm)	0-60 mph	20.5
	20-60 mph	19.1

Drive-by Noise (SAE J986a) 30 mph low gear dBA	
Mod. D	Not available
Mod. D- (2 mm)	76.4

Exhaust Smoke

The smoke trace obtained during the 1975 FTP cycle showed a maximum level at cold start of 30% obscuration with full load peaks of 20% cold and hot. High speed levels of 5% and idle levels of 7% for the Mod. D full lift condition.

For the 2 mm lift version the opacity of the exhaust was less; 10% at start and full load peaks, 4% at high speed conditions and 4% at idle.

Under driving conditions no excessive smoke was visible under any conditions. Some smoke was apparent at idle for both arrangements. Driving of the vehicle was unimpaired by either of the above EGR modulations.

10.6 Discussion of Results - Task 7

From the above results it can be seen that the constraints of the test programme stated in section 9.1 can each be met by one or more of the EGR modulations used. Other builds of EGR valve were possible but it was considered that no advantage would be gained by further testing.

The configurations of the EGR valve to meet the constraints are summarised in the table below which also gives the appropriate emission result and the range of EGR percentage (measured by air flow reduction) which was achieved with the EGR modulations from Task 6.

		EGR	Results gpm			EGR %	
Constraint	**Target**	**Mod.**	**HC**	**NOx**	**CO**	**Max.**	**Min.**
1	Min. EGR	D-(2mm)	1.705	1.52	1.329	10	0
2	HC .41 gpm	G	.406	.48	2.492	55	2
		C+	.382	.471	2.379	60	10*
3	85% load	C+	.382	.471	2.379	60	10
		G	.406	.48	2.492	55	2
		C+7°R	4.974	.32	6.129	60	10*
4	.3 to .4 gpm NOx	C+7°R	4.974	.32	6.129	60	10*
		C+4°R	1.053	.379	2.956	60	10*
5	1.0 gpm NOx	D	.226	.961	1.536	40	0

*Estimated 10% - no test data available.

The results above show that although very low NOx figures were achieved these were at the expense of large increases in the emission of HC and CO. Also, not shown in the above table was the greatly impaired driveability of the vehicle with the larger amounts of EGR which had to be applied, particularly noticeable at low speed steady state driving. At these conditions persistent misfire was apparent and with the retarded injection timing necessary for the lowest NOx builds, white smoke emissions were also present although black smoke under these retarded conditions was less of a problem.

Fuel economy of the vehicle was also considerably worsened by both EGR and retarded timings when compared with the zero EGR build of the vehicle, either N/A or T/C. However with the lower EGR builds for constraints numbers 1 and 5 the fuel consumption figures were comparable for the HFET but were approximately 16% worse for the 1975 FTP when compared with the original T/C version of the vehicle in Task 2.

The exhaust smoke opacity when observed under road driving conditions was worsened by the application of EGR but not excessively so. This was also evident on cold start up when very high instantaneous peaks were shown on the recording traces made during the 1975 drive cycles.

The acceleration of the vehicle was impaired for all configurations of the EGR valve apart from the minimum EGR levels for constraint No. 1. With the levels of EGR and injection retard required for constraint 4, the time for the accelerated from 0-60 mph was increased by 7 and 4 second respectively for 7 and 4 crank degrees injection timing retard.

Particulate emissions were high for each build of the EGR valve when compared with the zero EGR level for the turbocharged version of the vehicle. The lowest particulate level of .93 gpm for EGR Mod. C+ 7^o injection retard was almost twice the level of 0.5 gpm for the normal T/C version of the vehicle. A similar level was shown for the minimum EGR build for constraint No. 1 (Mod. D-). For the EGR modulation derived for 1 gpm NOx a particulate emission of 1.59 gpm was shown, more than three times that for the T/C vehicle and twice that recorded for the N/A version of vehicle without EGR.

Drive-by noise tests were not obtained for all of the EGR modulations but the results that were obtained showed noise levels to be higher than for the zero EGR versions. The lowest level of EGR produced a noise increase of 2 dBA, as did the EGR + 4^o retard condition. It was not possible to carry out noise tests for the 1 gpm or lowest possible NOx levels of EGR due to a prolonged period where road conditions were unsuitable.

Subjectively the noise of the vehicle was little changed from the original build on full acceleration drive-by conditions when the EGR valve was closed. However it was noticeable that induction noise was increased at light load conditions when the EGR valve effectively opened the unsilenced exhaust system into the engine inlet. Also cold combustion could be noisy and harsh under conditions of high EGR, although the normal effect of EGR, when the engine was hot, was to reduce combustion noise.

At idle conditions when the EGR valve was opened to the maximum, combustion was particularly quiet with a hot engine. Some mechanical noise was evident at idle however due to the self cleaning mechanism of the EGR valve causing a metallic rattle. This effect could be eliminated by modification to the valve.

For the highest levels of EGR for constraints 2, 3 and 4 the driveability of the vehicle was impaired at steady state low speed conditions because of persistant misfire. This was not apparent at maximum acceleration or at the conditions of lower rates of EGR. Driving of the 1975 FTP cycle was not affected although cold acceleration was impaired.

10.7 Conclusions - Task 7

These tests have shown that the achievement of a NOx emission level of below .4 gpm is not possible without increasing the HC and CO emissions greatly above the maximum permitted limit. Also greatly impaired are particulate emissions and vehicle performance.

The level of EGR required to reduce the NOx emissions to 1 gpm allowed the HC and CO emissions to remain below the legislated limits of .41 and 3.4 gpm. However particulate emissions were again very high under these conditions.

For all conditions except for the minimum EGR the fuel consumption was impaired.

Figure 159 shows the installation of the EGR valve in the vehicle with the air cleaner removed, the actuator being shown set for Mod. D to give 1.0 gpm NOx.

Instructions for varying the build of the valve using a set of change parts are the subject of a separte document (DP.78/636).

11. GENERAL CONCLUSIONS

The aims and objectives of the work detailed in this report were to demonstrate a system of exhaust gas recirculation for light duty diesel engines. These objectives were in the form of target constraints of emission and performance of a Mercedes 300D vehicle fitted with a modulated EGR system.

Initial tests on a standard version of the vehicle were carried out and the emissions, performance, noise and fuel consumption were assessed to provide base line data. Similar data from the vehicle with a retrofitted turbocharger were obtained, the object of the turbocharger being to provide excess air and not to improve the engine output. These base line vehicle tests were satisfactorily concluded and the results indicated levels of emissions and performance comparable with similar diesel powered vehicles.

At the time of the tests the level of boost employed, and therefore the quantity of excess air, was relatively low due to the low limit to the cylinder pressure thought to apply. Higher levels of boost, which, in the light of a revised higher cylinder pressure limit could have been employed were not investigated, as evidence showed that a further worsening of vehicle performance and NOx emission would result.

It would appear that the original concept of using the turbocharger to supplement any loss of performance caused by the application of EGR may have been inappropriate, the fitting of the turbocharger in itself causing a loss in performance. Tests on the engine with EGR and no turbocharger were not carried out and therefore no conclusions in this respect can be drawn. However there is little doubt that the use of the turbocharger was of considerable assistance in promoting even distribution of the EGR by the chosen method of its introduction into the compressor intake.

For the most efficient application of EGR, tests to determine areas of the 1975 FTP cycle which contributed disproportionately high levels of NOx emissions to the weighted results were carried out. The conclusions derived from these tests indicated that all areas of the FTP cycle would require treatment with EGR if the lowest NOx levels of the target constraints were to be achieved.

Calibration of the engine on the test bed was carried out over the range of loads and speeds occurring in the 1975 drive cycle with both naturally aspirated and turbocharged versions of the engine. These tests were followed by calibration of the turbocharged version of the engine with a wide range of exhaust gas recirculation.

EGR was introduced into the compressor intake of the turbocharger and was initially controlled manually by means of a butterfly valve regulating the exhaust gas flow, with a second butterfly valve in the air inlet to create an artificially high intake depression if required.

From the EGR response of the engine various theoretical modulations were derived to enable computer simulation to be obtained of the possible effect on vehicle exhaust emissions. To establish the validity of the computer program the simulation of vehicle emissions without EGR was made from the steady state test bed results. The conclusions of these predictions indicated that accurate forecasting of vehicle emissions would be difficult. The results would be sufficient to indicate trends however, which would allow thoeretical modulations to be applied to the computer program.

To simplify the application of modulated EGR to the engine a new EGR valve, with a mechanically operated actuator, was constructed. With this valve various modulations of EGR were applied to the engine and computed to obtain simulated vehicle emission levels as above. It was considered that these modulations would cover the target constraints if applied to the vehicle. The design of the EGR valve was such as to be able to cover a large range of modulations by variations to its internal components.

The installation of the EGR system into the vehicle was carried out to assess the modulations from the test bed in practice. Tests carried out with these modulations and variations of injection timing showed that all the constraints applicable could be achieved. The lowest level of NOx achieved was .32 gpm. This was achieved by heavily retarding the injection and by applying EGR at full load thus causing a reduction in vehicle performance. Under these conditions the HC and CO emissions were above the legislated limit and the driving of the vehicle was severely affected due to misfire at steady speeds below 40 mph.

With a level of EGR modulated to achieve 1.0 gpm NOx, HC and CO levels were within reasonable limits, and driveability was not affected. Noise and performance were however inferior to those of the original vehicle.

For any condition of EGR the particulate emissions of the vehicle was severely affected, being increased up to twice the value recorded for the original N/A version of the vehicle.

During the EGR tests on the vehicle approximately 500 miles were driven, the effect of such a low mileage on carbon deposits was not expected to be great and no inspection of the engine was carried out during this period.

During test bed calibration a total of approximately 96 hours was run at various levels of EGR. At 45 hours and 96 hours the turbocharger compressor was cleaned of a deposit of sooty, oily carbon. Such deposits were also present within the inlet manifold and ports. Some deposits were also observed on the back of the inlet valves and particularly in parts of the inlet manifold and turbocharger compressor which were not scoured by rapid air flows.

The above observations do not affect the main conclusions of these tests which have shown that a) .4 gpm NOx can be achieved if no other considerations are taken into account, b) 1 gpm NOx can be achieved with less detriment to other parameters, c) particulate emissions were severely increased by EGR, d) fuel economy was adversely affected by EGR, e) durability of the intake system of the engine would be adversely affected by EGR.

A summary chart of the replicated vehicle results is shown in Appendix 1.

DAP/SCS

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APPENDIX I

SUMMARY OF VEHICLE TEST RESULTS

Vehicle Build	Gaseous Emissions gpm			Part	Fuel mpg (US)		Noise dBA	Acceleration Seconds (mph)		
	HC	NOx	CO	gpm	CVS	HEFT		0-40	0-60	20-60
As-received	.183	1.66	.94	.8	24.3	29.95	74.2	9.6	21.2	18.7
Turbocharged	.14	1.75	.94	.5	23.8	25.6	74.5	9.9	22.4	19.2
EGR Modulation G	.395	.528	2.408	1.11	19.47	24.94	78.0*	10.6	23.5	20.1
EGR Modulation C+	.382	.471	2.379	-	19.95	-	-	-	-	-
EGR Modulation C+ 7° Retard	4.974	.32	6.129	.93	17.15	-	-	11.6	28.6	22.8
EGR Modulation C+ 4° Retard	1.053	.379	2.956	1.228	18.86	24.43	76.2	11.0	25.3	22.4
EGR Modulation D	.226	.961	1.563	1.59	20.08	25.78	-	10.2	22.6	19.1
EGR Modulation D- (7 mm lift)	.245	1.004	1.392	-	20.17	-	-	-	-	-
EGR Modulation D- (2 mm lift)	.171	1.52	1.329	.964	20.28	25.87	76.4	9.4	20.5	19.1

* Artifically high noise level - no retest figure available.

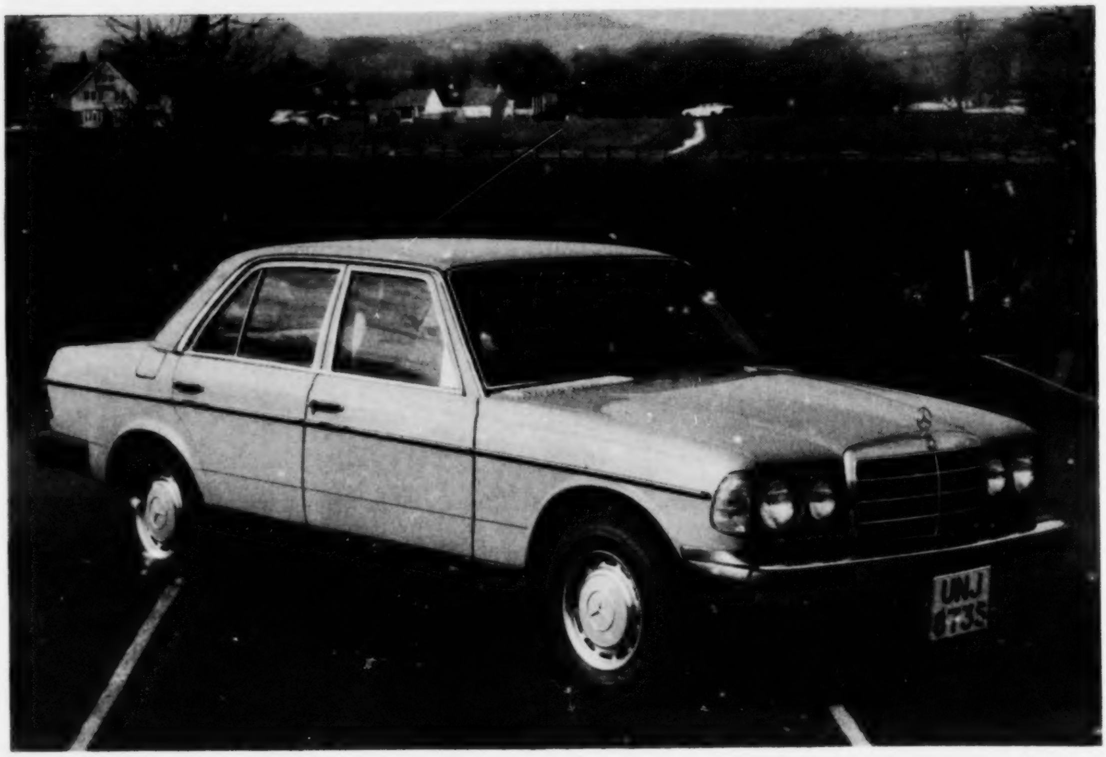
APPENDIX II

FUEL SPECIFICATION (FROM BRITISH STANDARD 2869:1970)

DIESEL FUEL CLASS A1

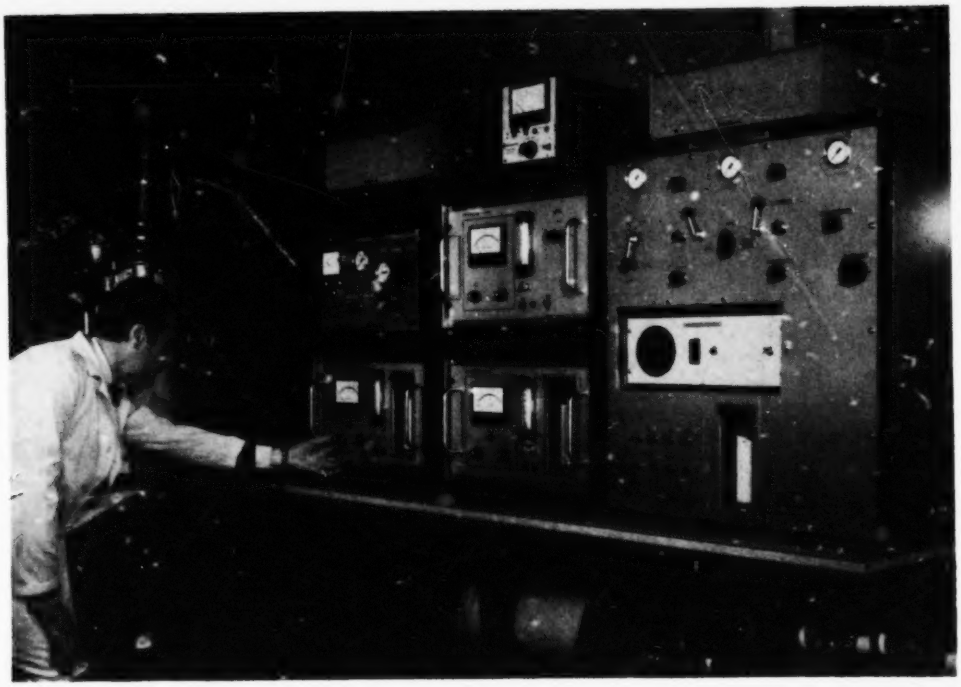
Viscosity, kinematic at 37.8°C (100°F), centistokes	min.	1.6
	max.	6.0
Cetane number, min.		50
Carbon residue, Ramsbottom, % by mass, max.		-
Carbon residue, Ramsbottom, % by mass, on 10% residue, max.		0.2
Distillation, recovery at 357°C (675°F), % by volume, min.		90
Flashpoint, closed, Pensky-Martens, min.		55°C (130°F)
Water content, % by volume, max.		0.05
Sediment, % by mass, max.		0.01
Ash, % by mass, max.		0.01
Sulphur content, % by mass, max.		0.5
Copper corrosion test, max.		1
Cloud point, max.	Summer	0°C (32°F) March/Nov. inclusive
	Winter	-7°C (20°F) Dec./Feb. inclusive
Pour point, max.		-

FIGURE 1



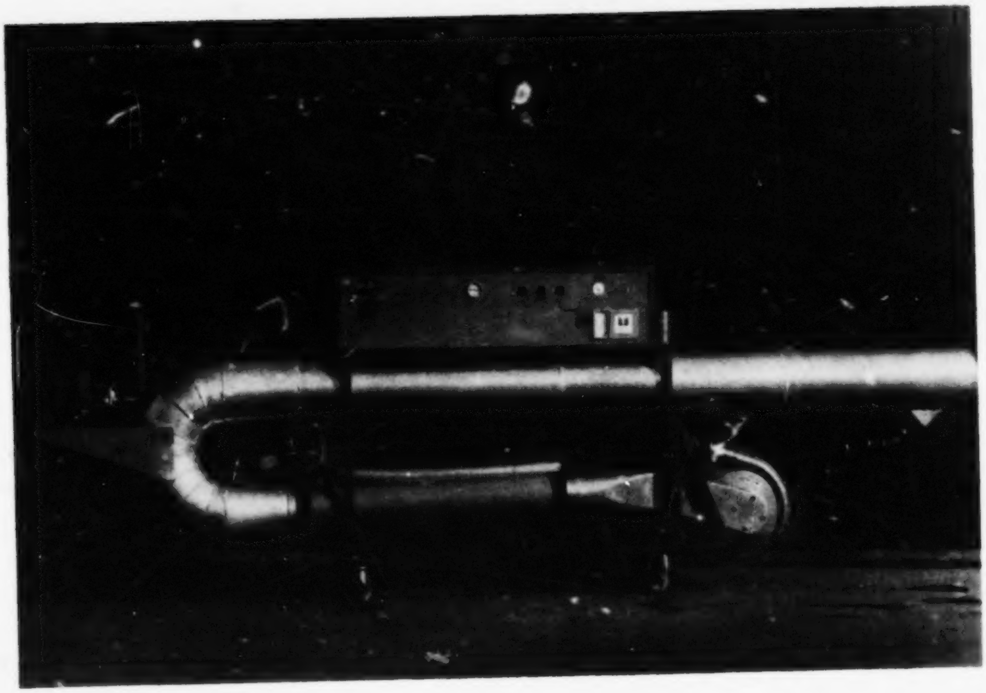
Mercedes 300D Light Duty Diesel Vehicle

FIGURE 2



Ricardo Portable Gaseous Emissions Measuring Apparatus

FIGURE 3



Ricardo Portable Particulates Measuring Apparatus

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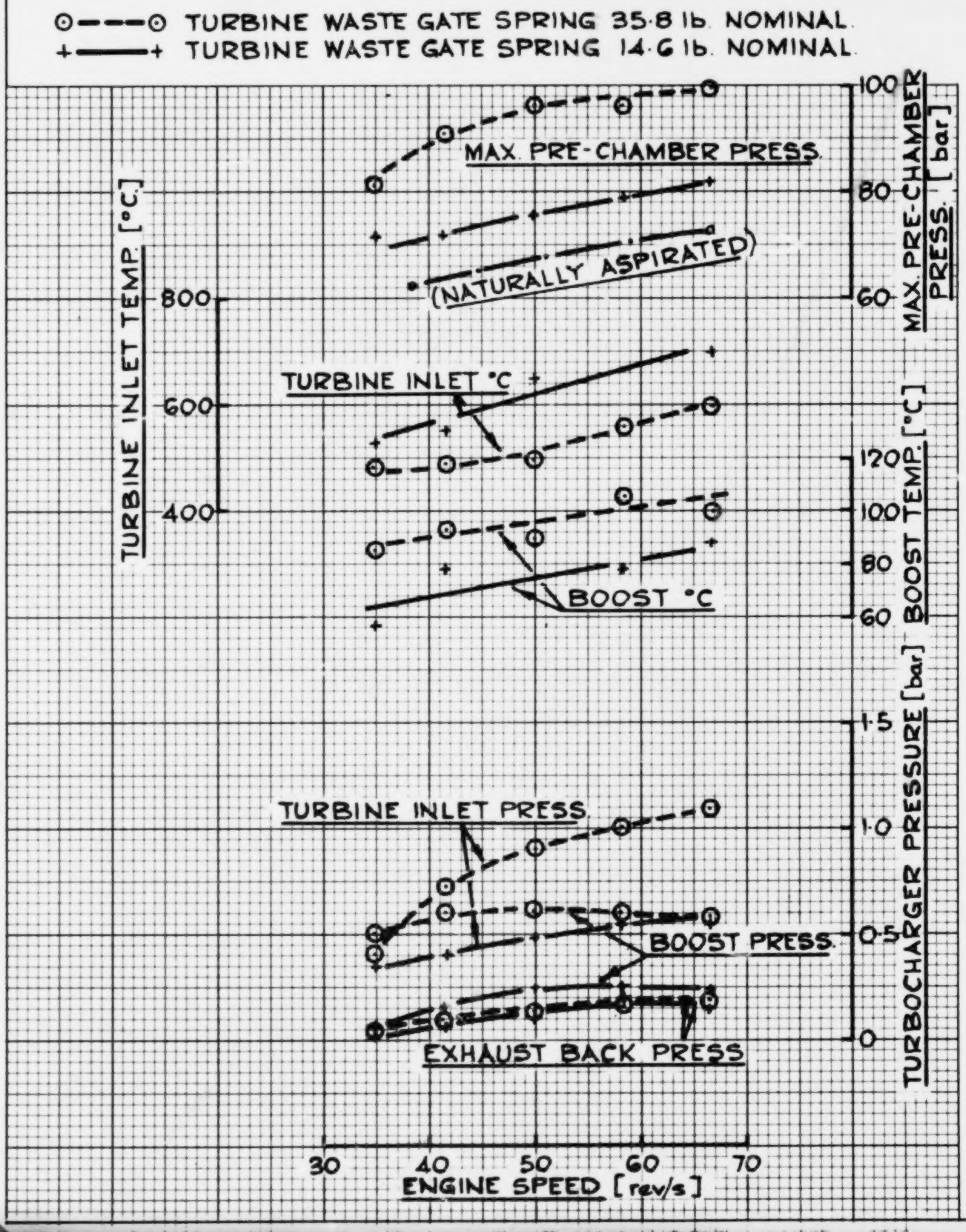
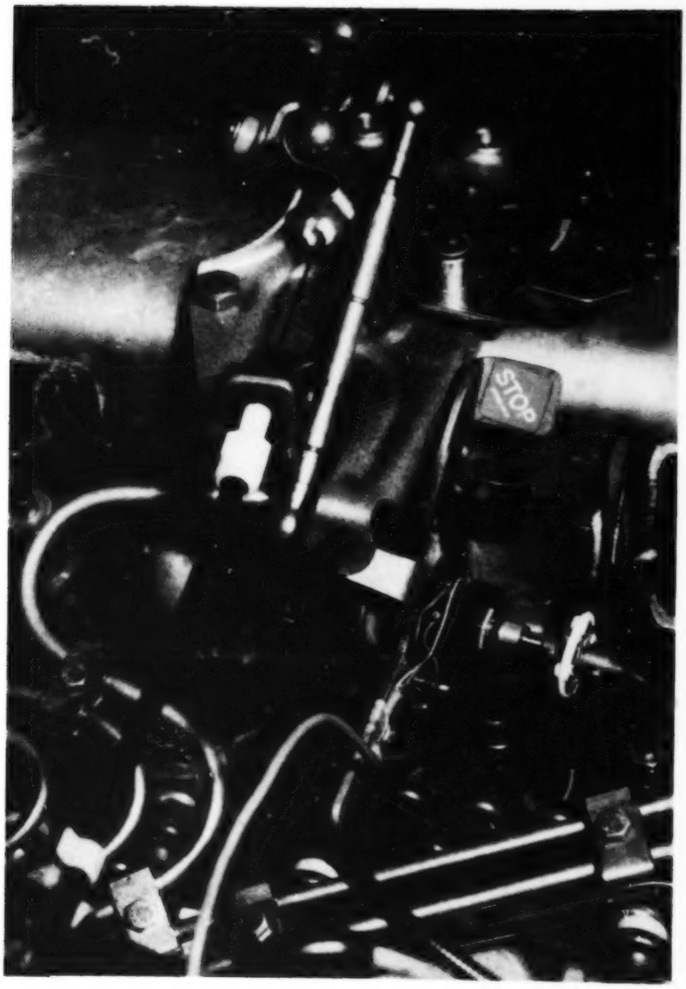
FIG. No. 4
Drg. No. D34906
Date APRIL. '77
Engine Curve No. 1a

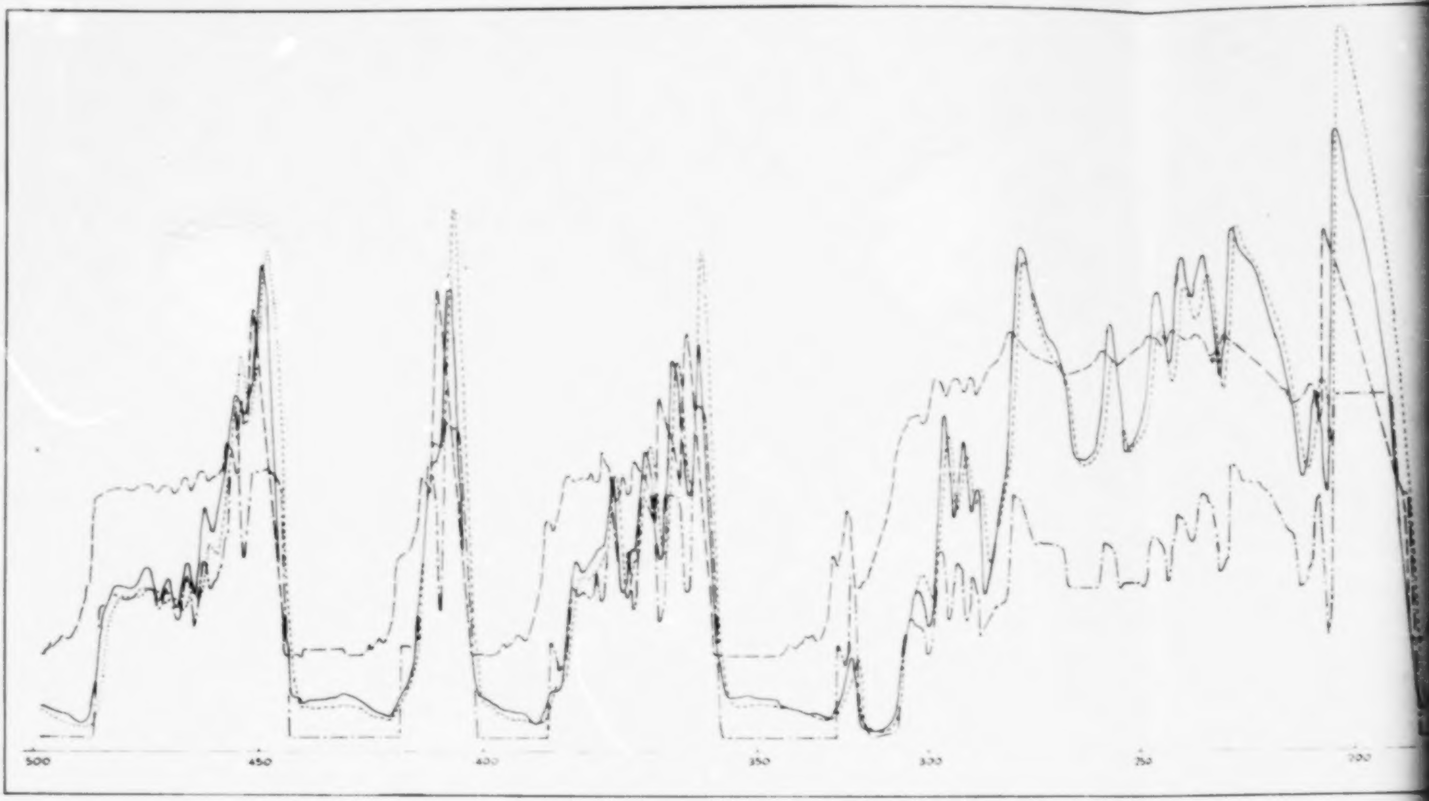
EPA MODULATED EGR STUDY

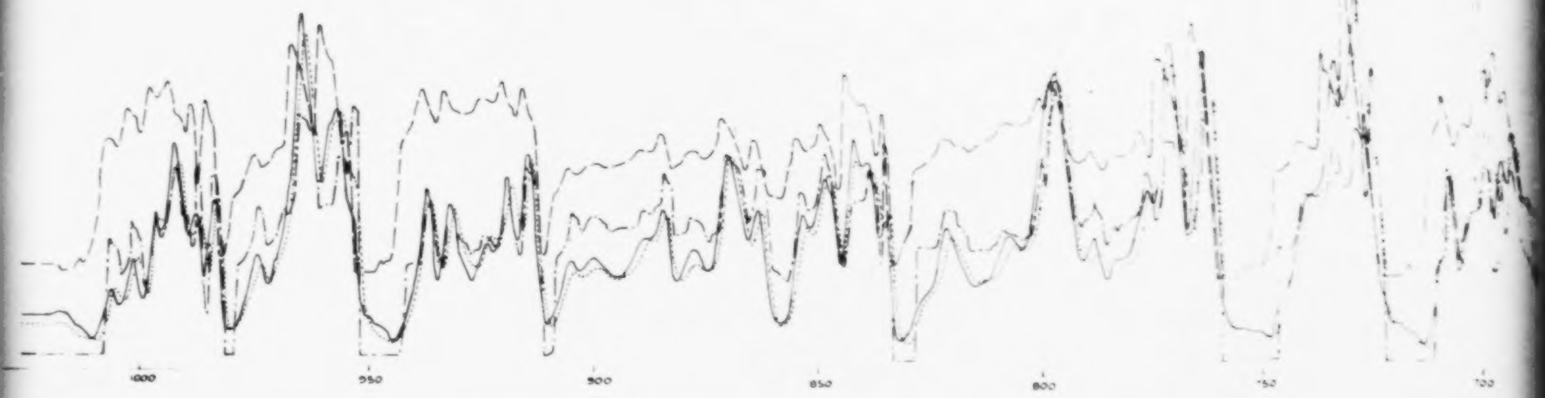
CURVES SHOWING TURBOCHARGER PERFORMANCE AND PRE-CHAMBER PRESSURES ON MERCEDES-BENZ 300 D CAR AT FULL LOAD CONDITIONS. NO EXHAUST SILENCERS





Installation of Injection Pump
Linkage Movement Transducer

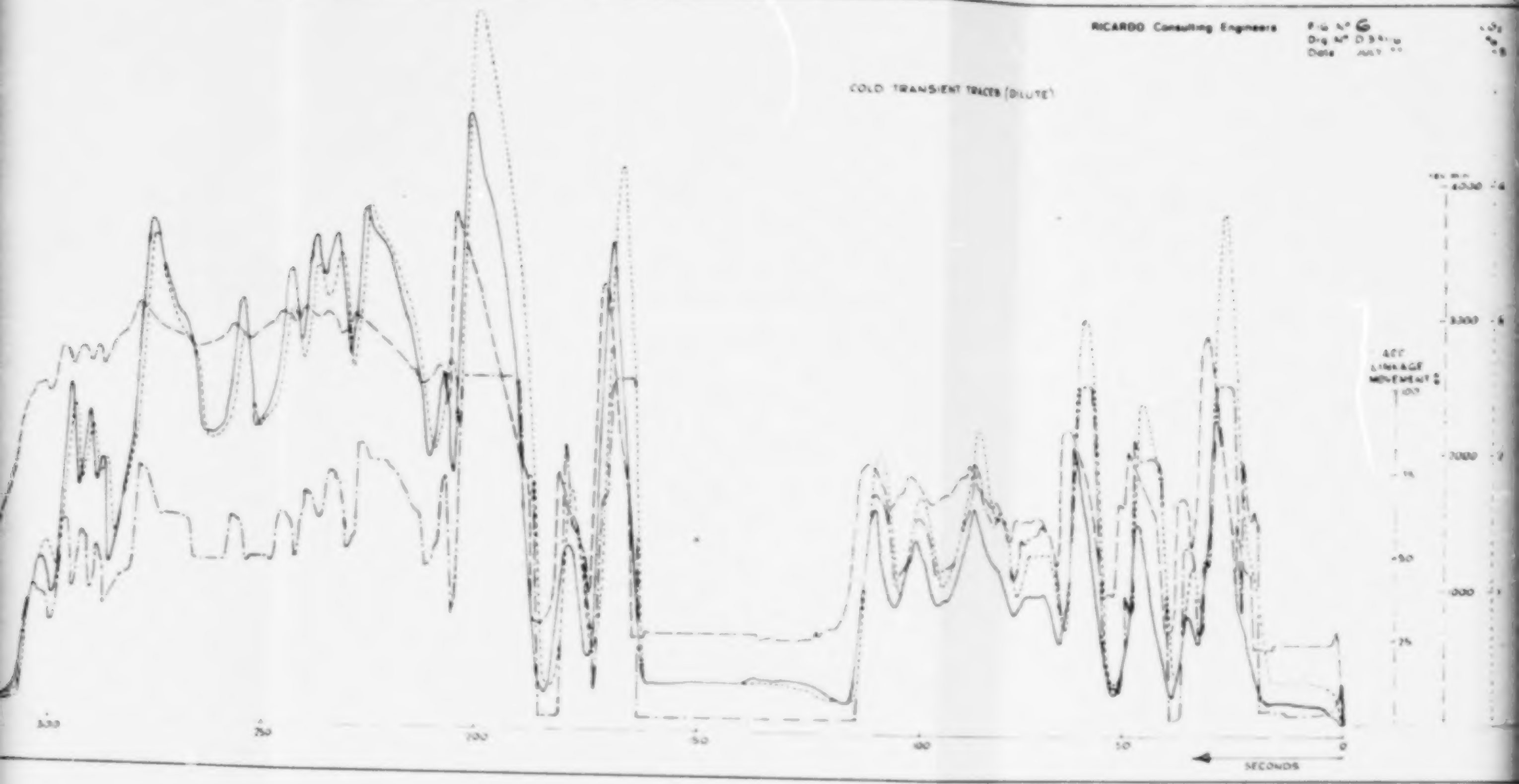




A

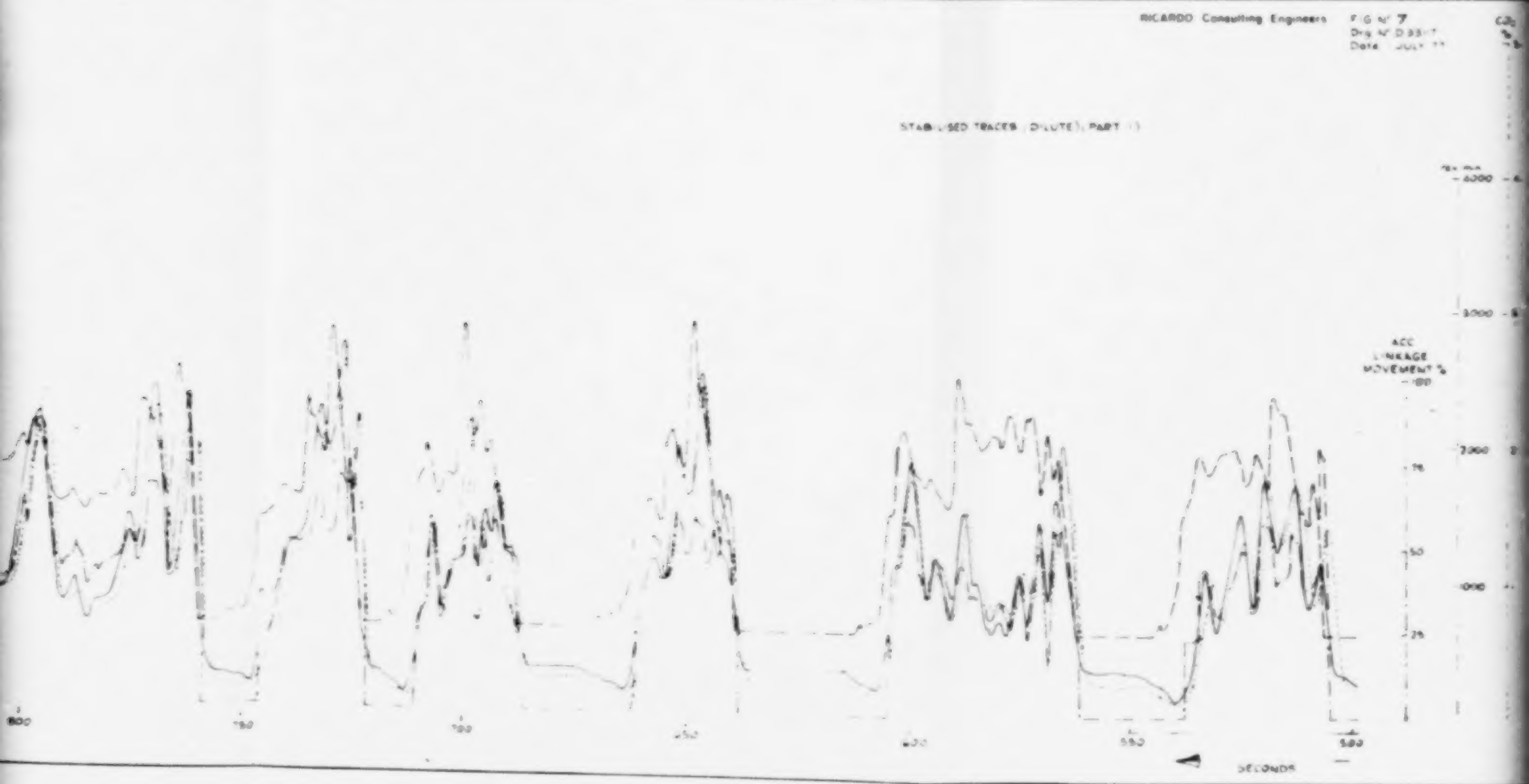
RICARDO Consulting Engineers
FIG No 6
Drg No D 33[illegible]
Date JULY 77

COLD TRANSIENT TRACES (DILUTE)



RICARDO Consulting Engineers
FIG No 7
Drg No D 33[illegible]
Date JULY 77

STABILISED TRACES (DILUTE) (PART 1)



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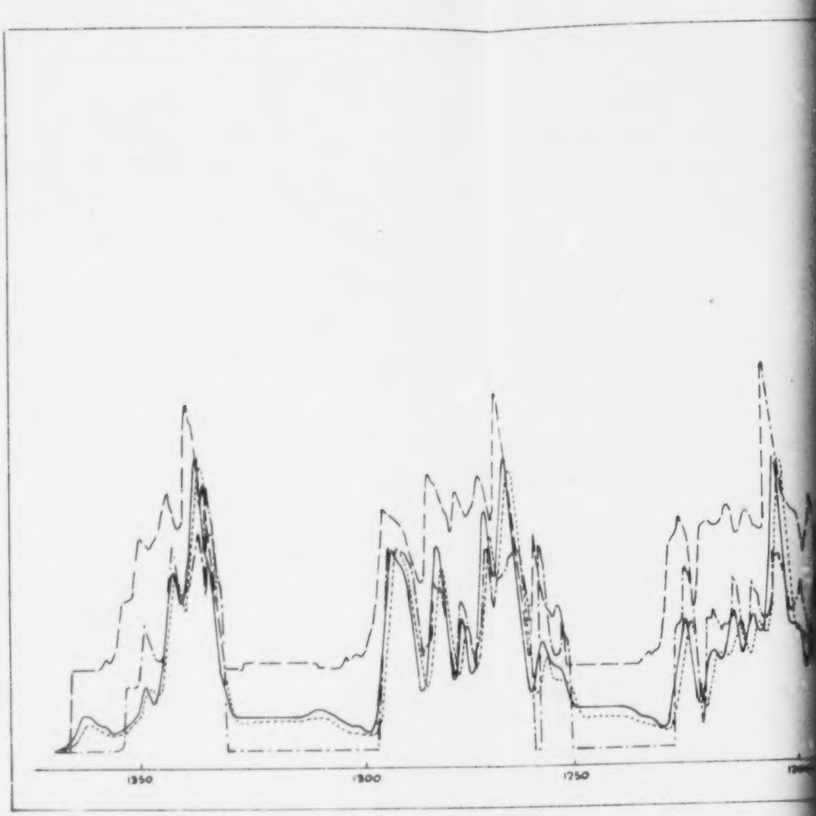

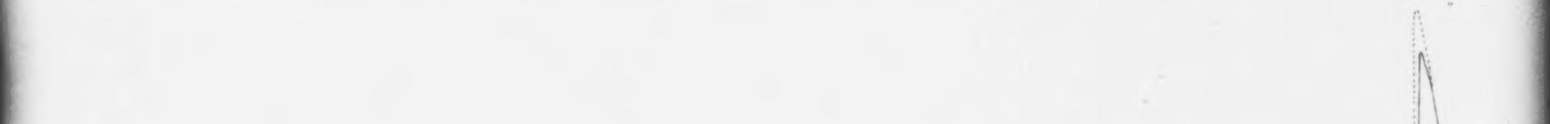

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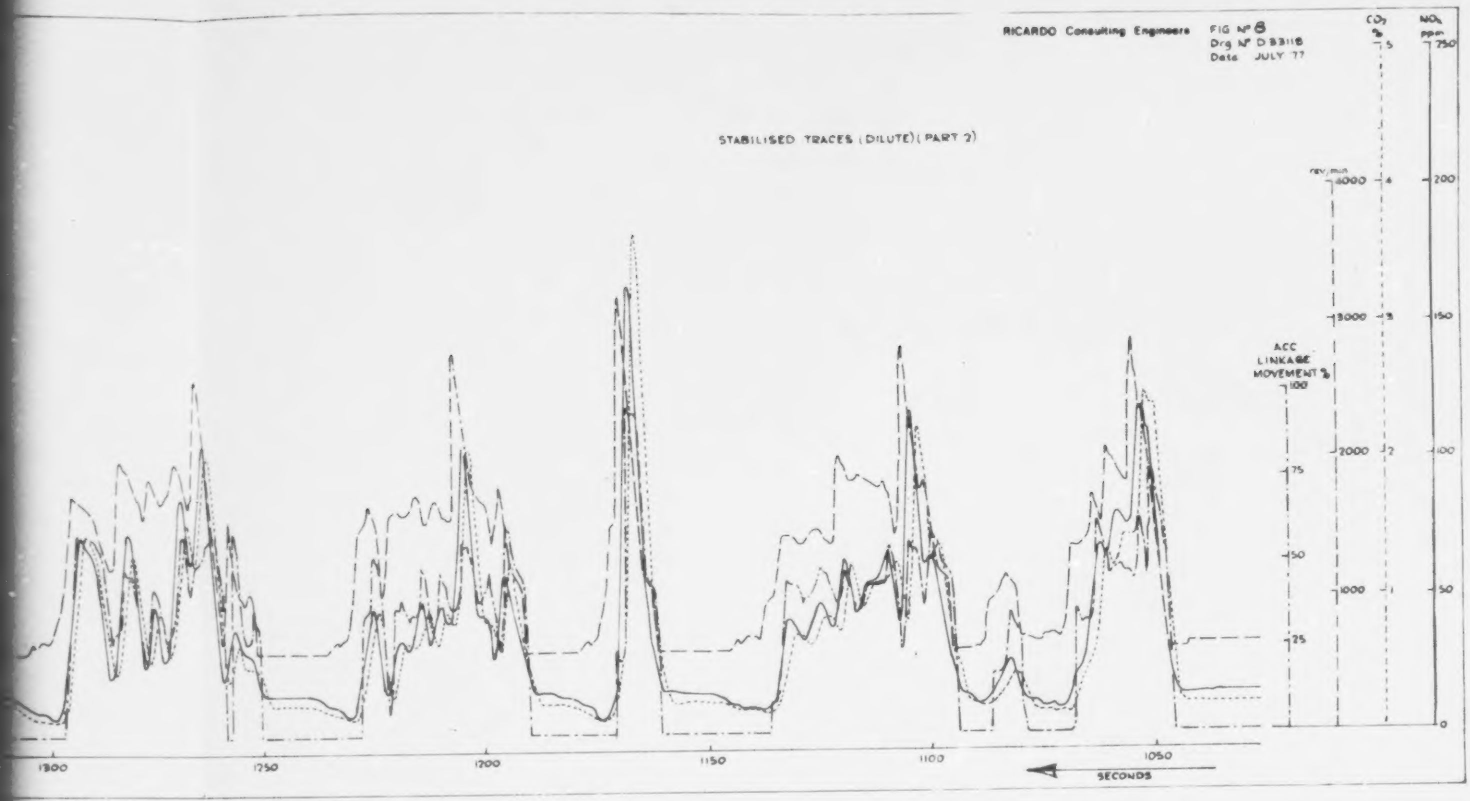

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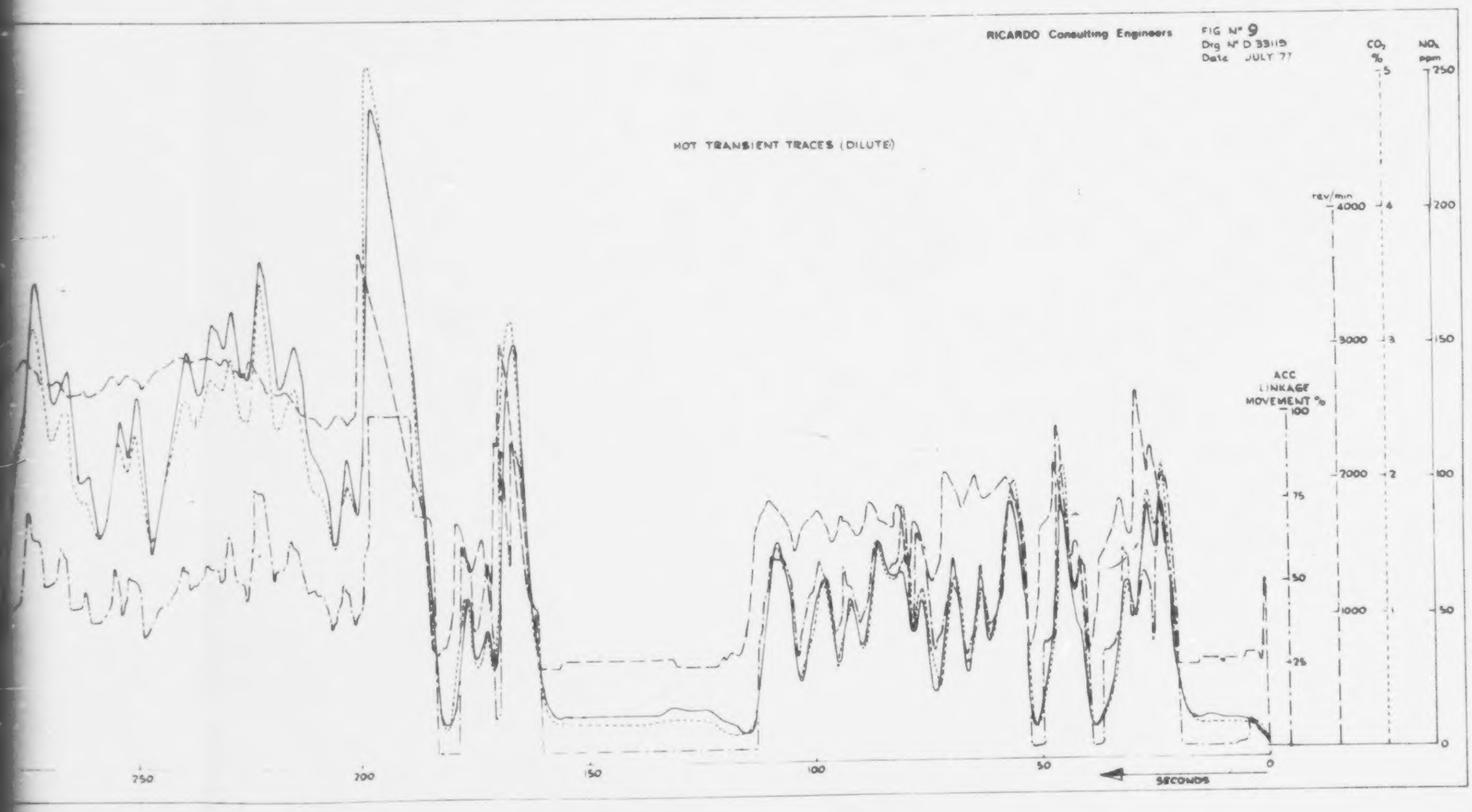
FIG Nº 8
Drg Nº D 33118
Date JULY 77

STABILISED TRACES (DILUTE) (PART 2)



RICARDO Consulting Engineers
FIG Nº 9
Drg Nº D 33119
Date JULY 77

HOT TRANSIENT TRACES (DILUTE)

B

RICARDO CONSULTING ENGINEERS

FIG. No. 10

Drg. No. D 33120

Date JULY '77

EPA MODULATED EGR STUDY.
GRAPH SHOWING RELATIONSHIP BETWEEN NO_x EMISSION AND ACCELERATOR LINKAGE POSITION FOR COLD TRANSIENT PHASE OF FTP.

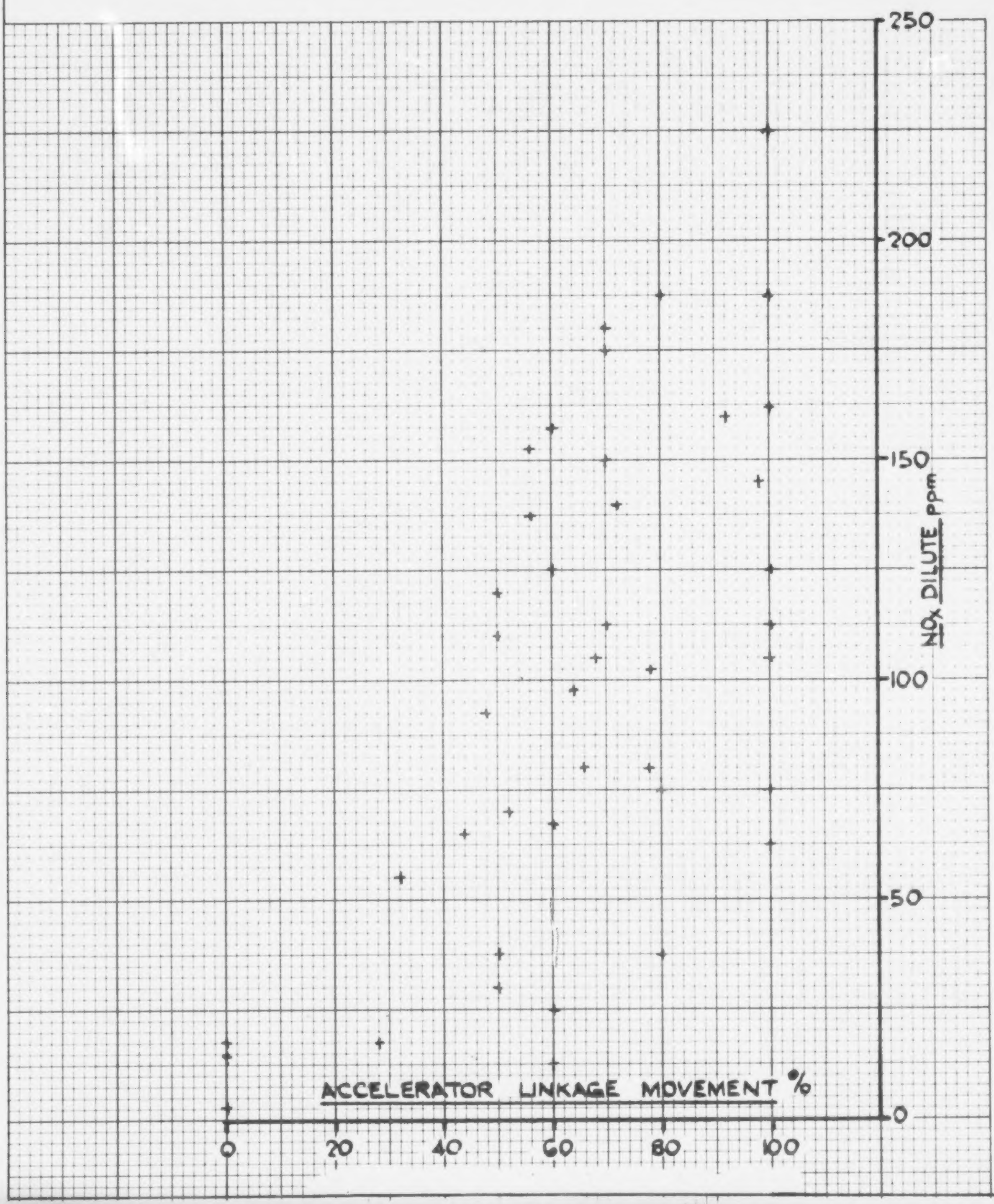


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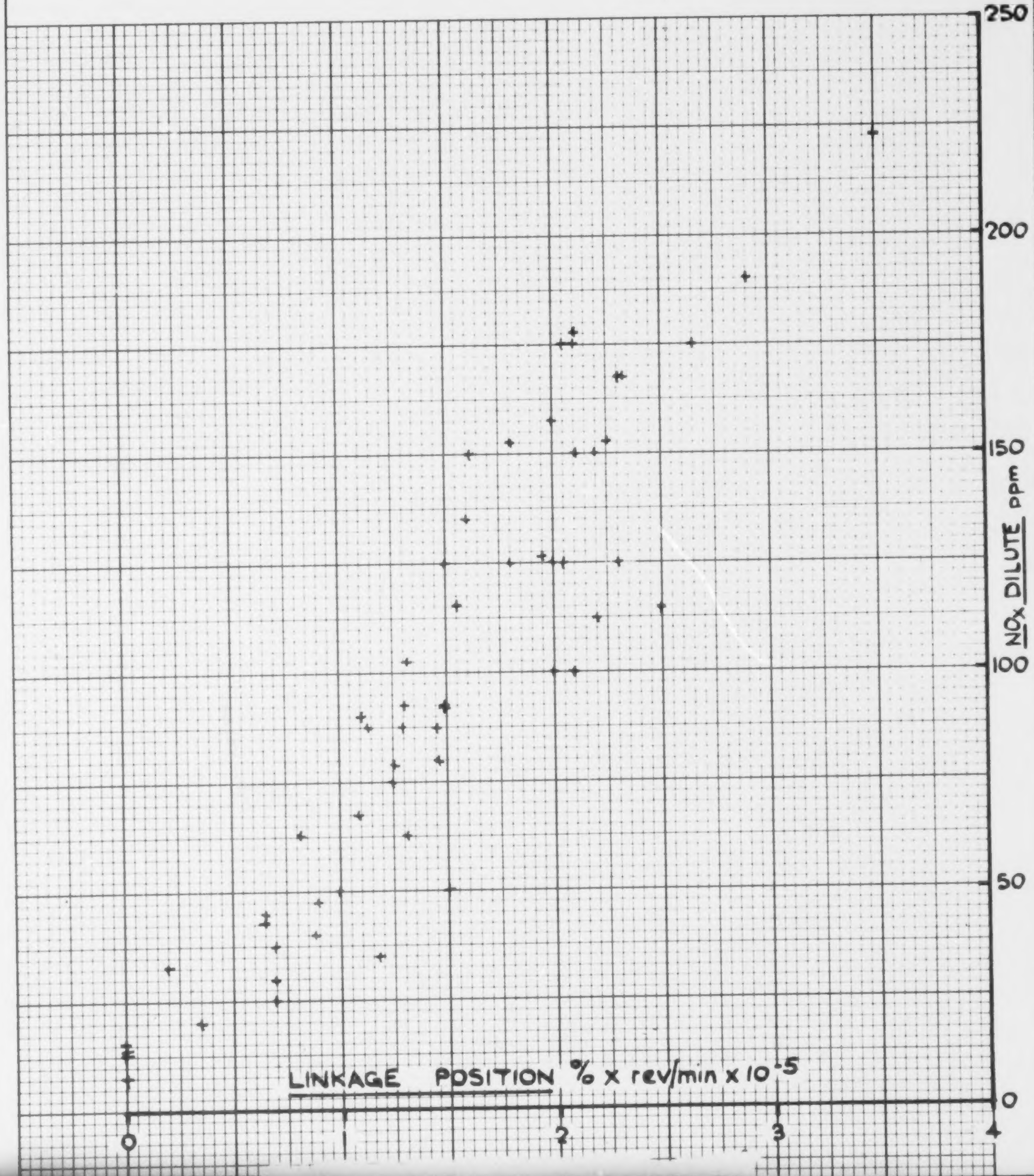
FIG. No. 11

Drg. No. D. 33121

Date JULY '77

EPA MODULATED EGR STUDY.

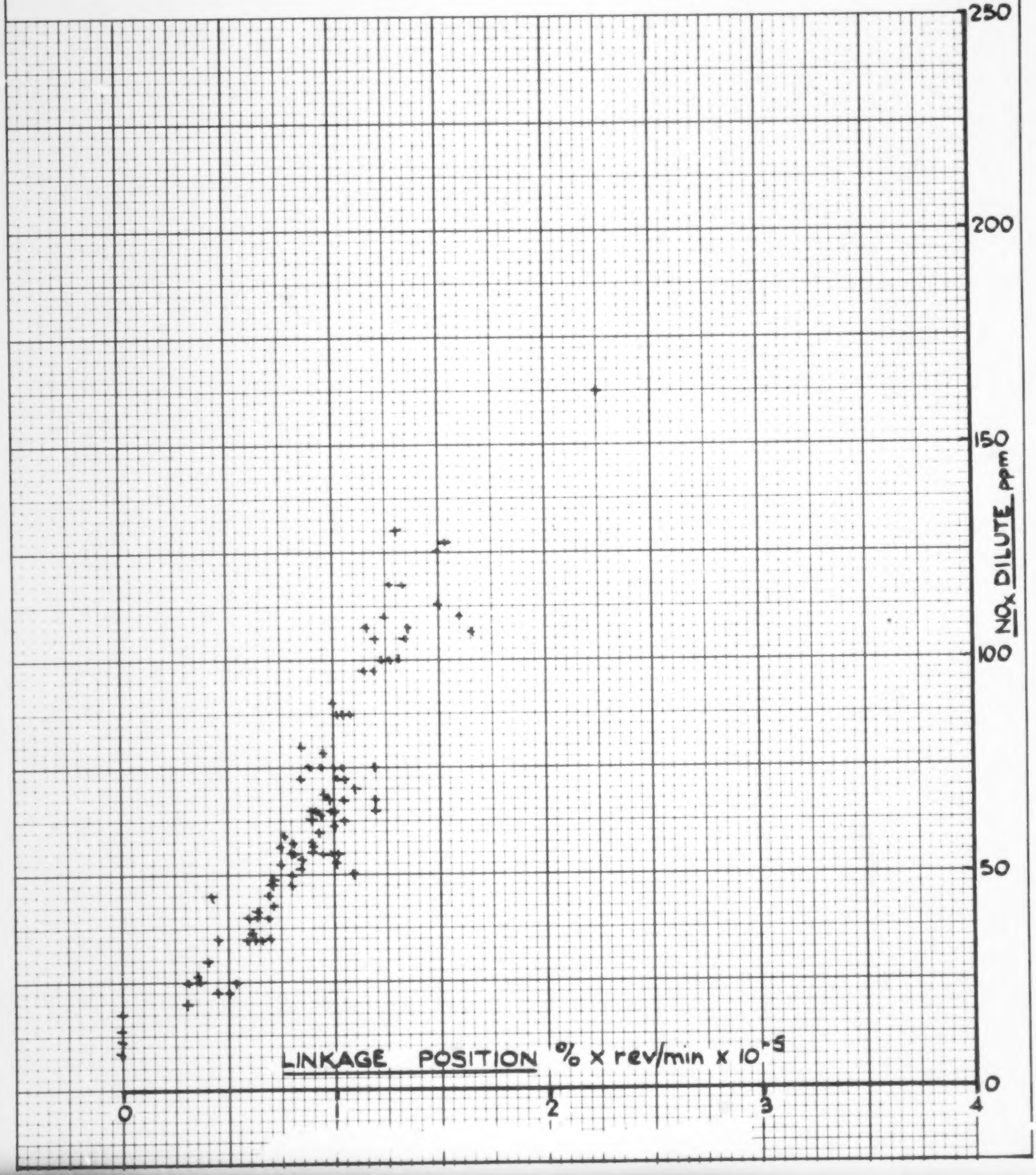
GRAPH SHOWING RELATIONSHIP BETWEEN NO_x EMISSION AND COMBINED LINKAGE POSITION AND ENGINE REVOLUTIONS FOR COLD TRANSIENT PHASE OF FTP



RICARDO CONSULTING ENGINEERS

FIG. No. 12
Drg. No. D 33122
Date JULY '77

EPA MODULATED EGR STUDY.
GRAPH SHOWING RELATIONSHIP BETWEEN NOx EMISSION AND COMBINED LINKAGE POSITION AND ENGINE REVOLUTIONS FOR STABILISED PHASE OF F.T.P.



RICARDO CONSULTING ENGINEERS

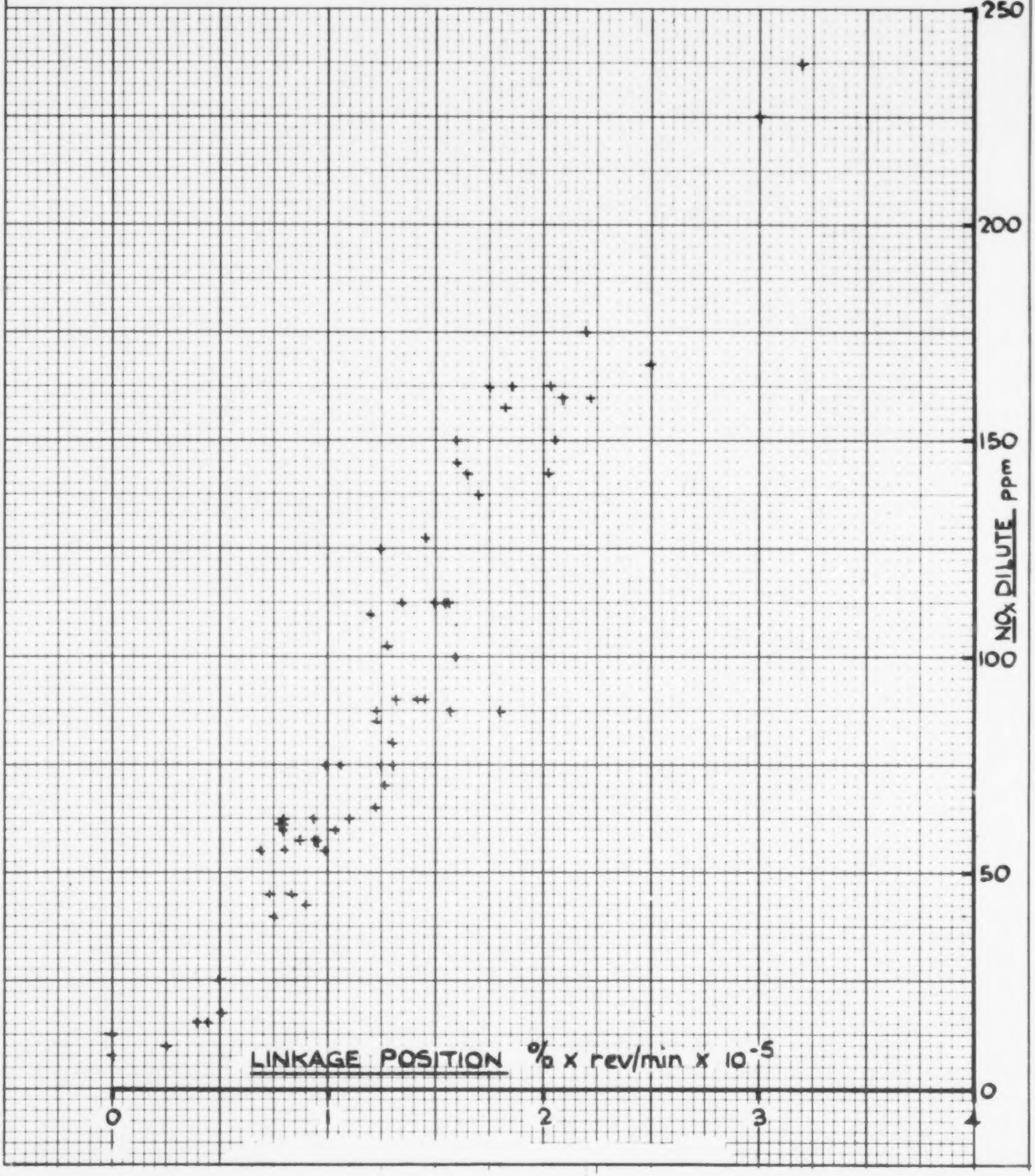
FIG. No. 13

Drg. No. D.33123

Date JULY '77

EPA MODULATED EGR STUDY

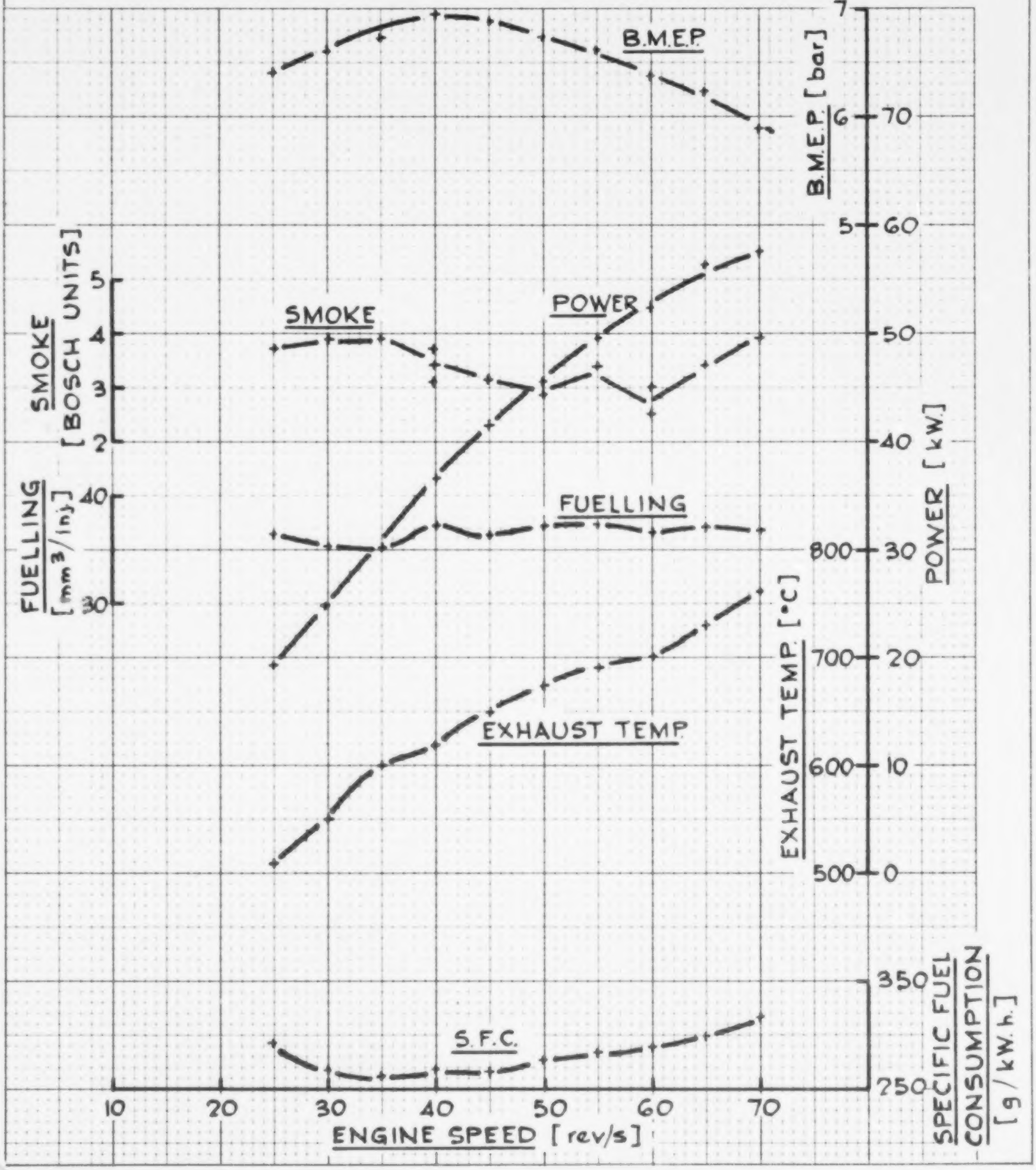
GRAPH SHOWING RELATIONSHIP BETWEEN NO_x EMISSION AND COMBINED LINKAGE POSITION AND ENGINE REVOLUTIONS FOR HOT TRANSIENT PHASE OF FTP



RICARDO CONSULTING ENGINEERS

FIG. No. 14
Drg. No. D34907
Date AUG.'77
Engine Curve No. 1

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm x 92.4 mm x 5 CYL.
AS RECEIVED POWER CURVE



RICARDO CONSULTING ENGINEERS

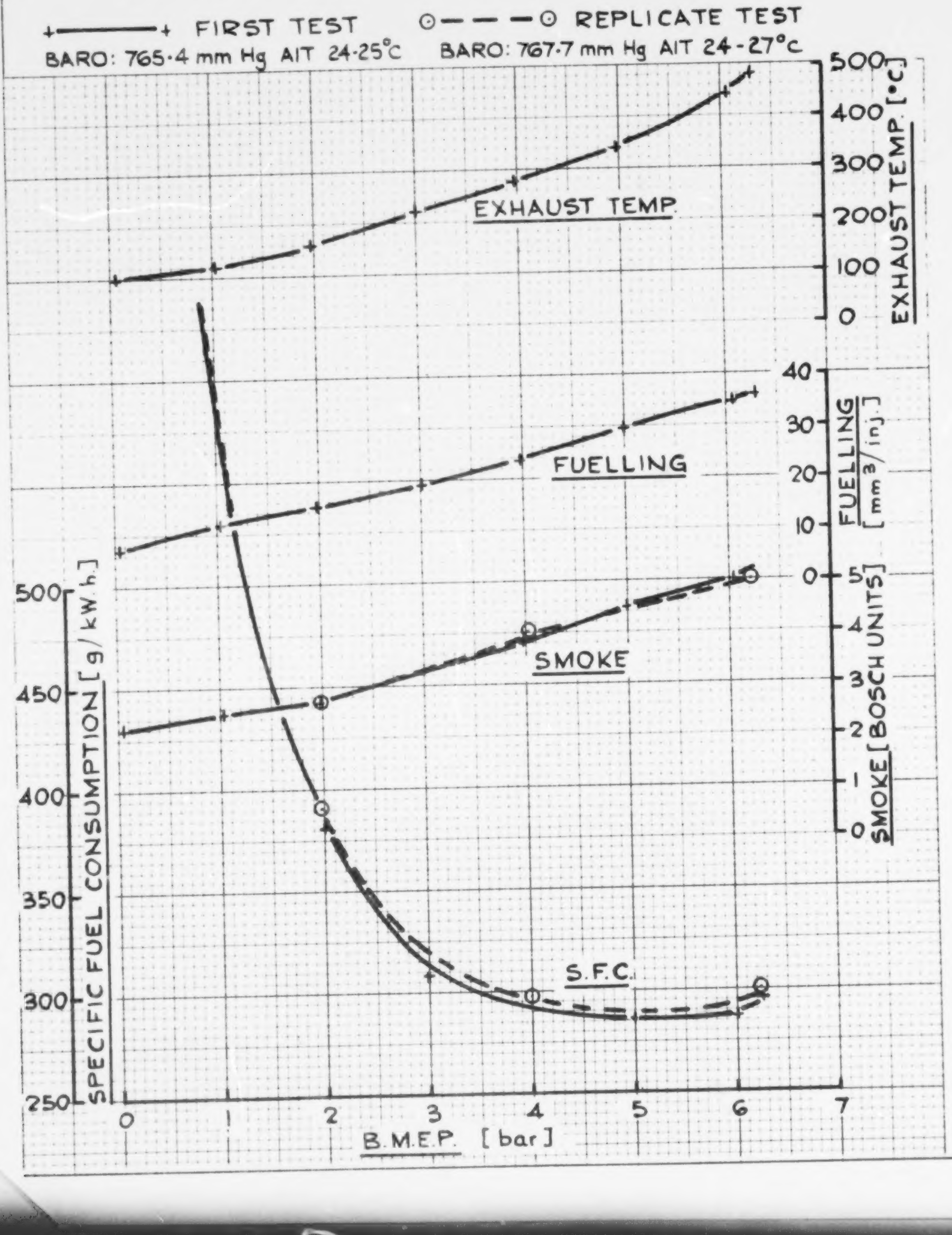
FIG. No. 15
Drg. No. D34908
Date AUG.'77
Engine Curve No. 2

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92.4 mm x 5 CYL.

LOAD RANGE PERFORMANCE AT 15 rev/s.

STANDARD AS RECEIVED BUILD



RICARDO CONSULTING ENGINEERS

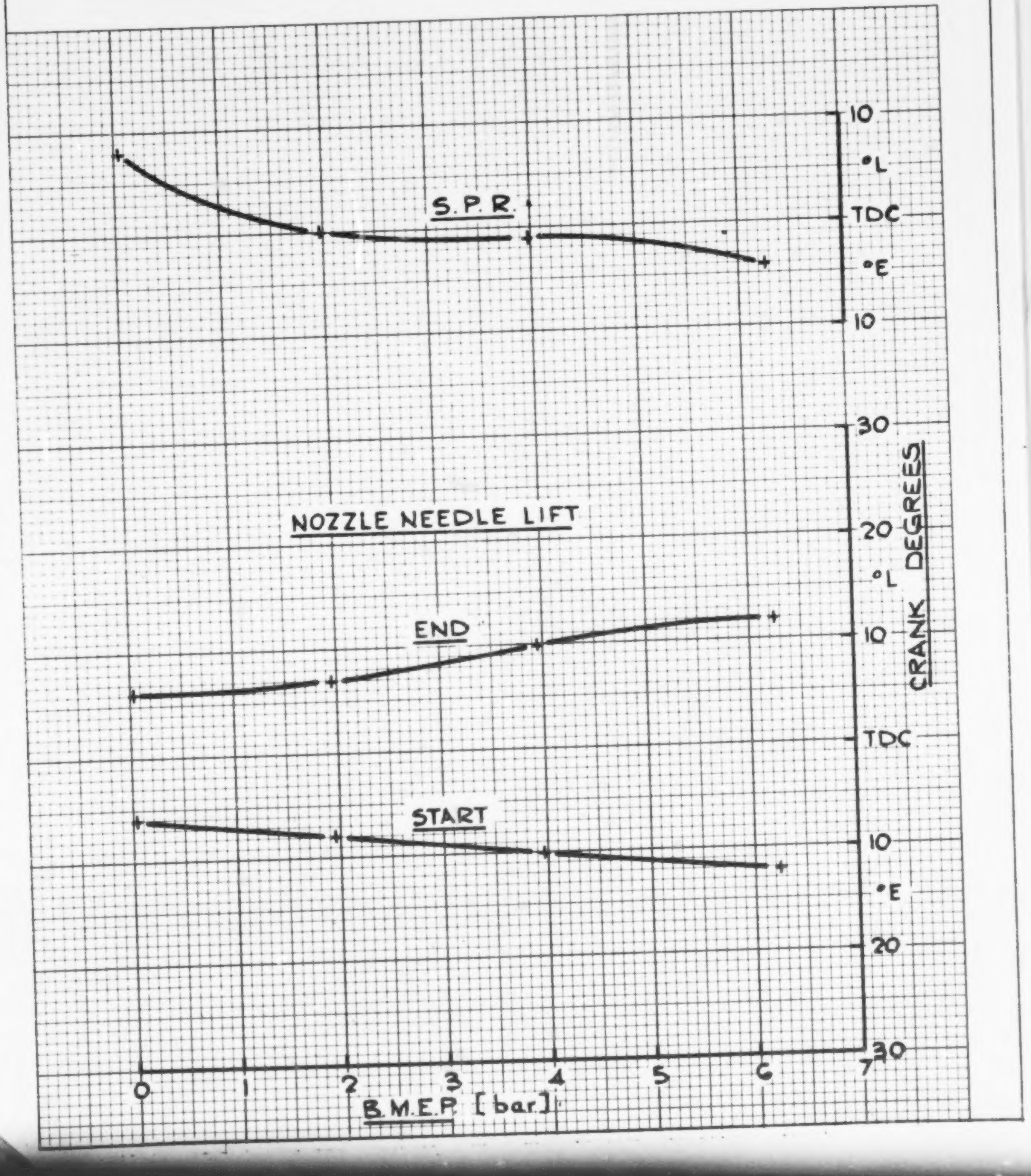
FIG. No. 16
Drg. No. D34909
Date AUG. '77
Engine Curve No. 3

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 15 rev/s

STANDARD AS RECEIVED BUILD

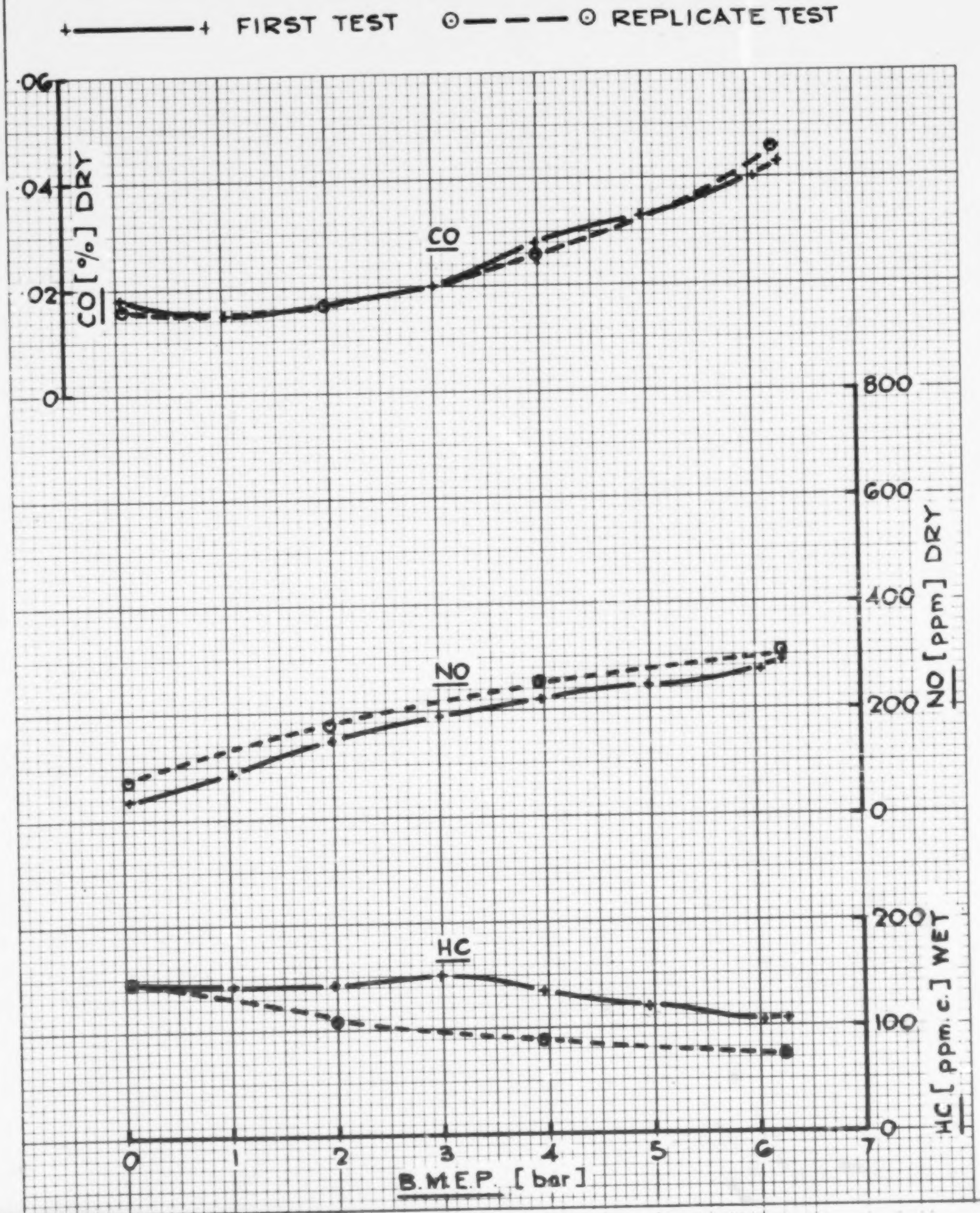


RICARDO CONSULTING ENGINEERS

FIG. No. 17
Drg. No. D34910
Date AUG. '77
Engine Curve No. 4

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL
HC, NO AND CO EMISSIONS AT 15 rev/s

STANDARD AS RECEIVED BUILD

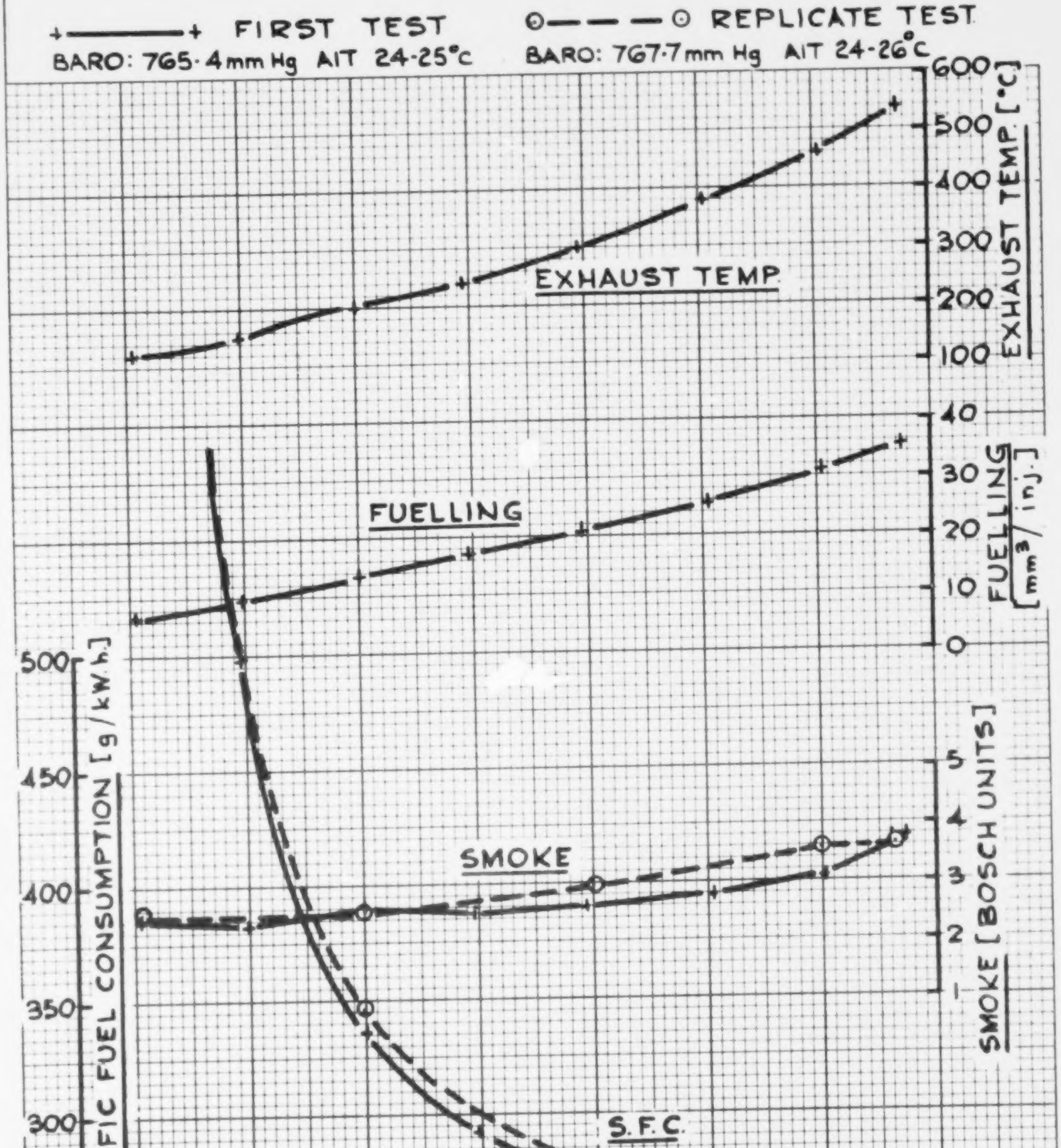


RICARDO CONSULTING ENGINEERS

FIG. No. 18
Drg. No. D34911
Date AUG. '77
Engine Curve No. 5

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm × 92·4 mm × 5 CYL.
LOAD RANGE PERFORMANCE AT 25 rev/s

STANDARD AS RECEIVED BUILD

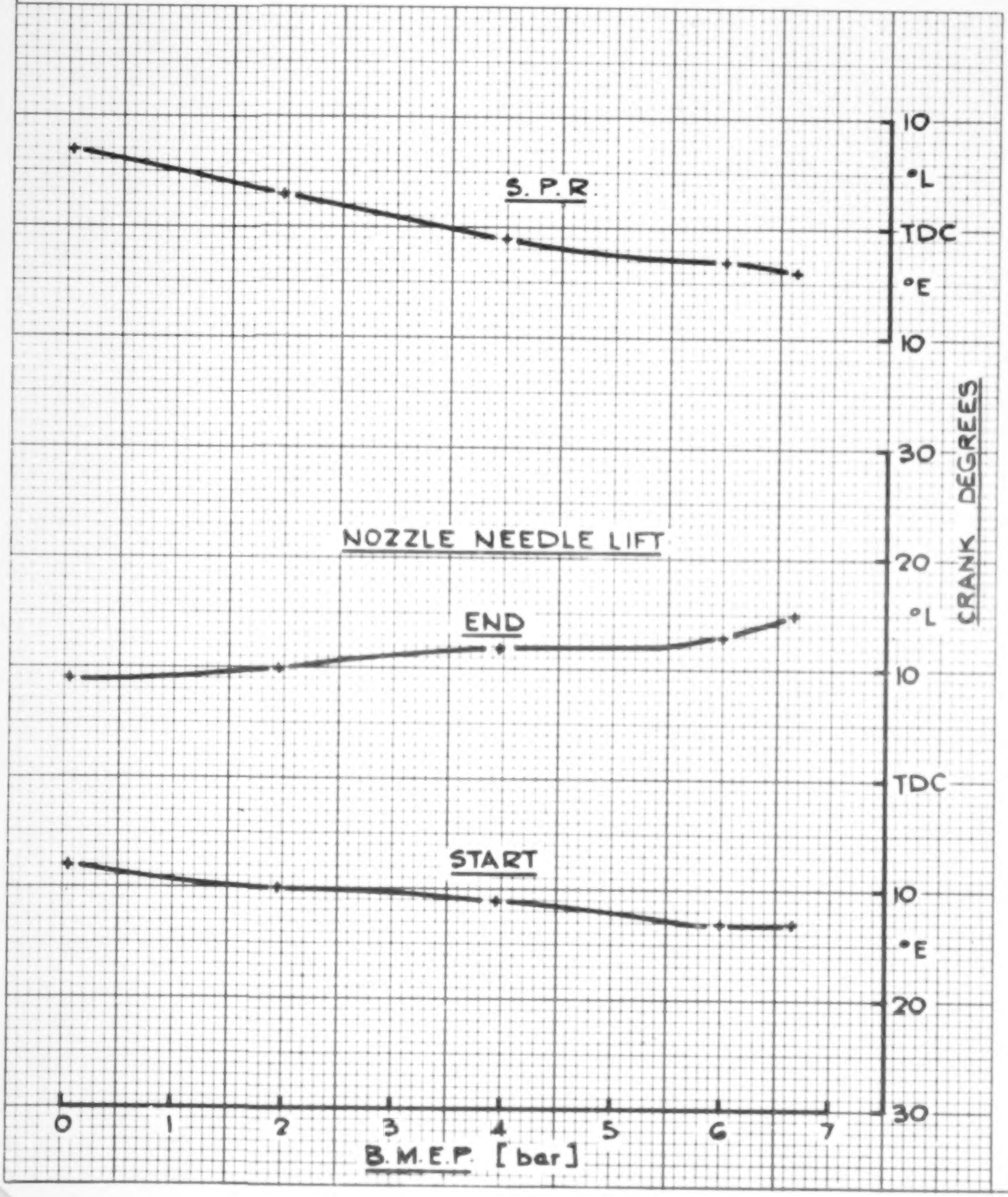


RICARDO CONSULTING ENGINEERS

FIG. No. 19
Drg. No. D34912
Date AUG. '77
Engine Curve No. 6

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5 CYL.
DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 25 rev/s.

STANDARD AS RECEIVED BUILD

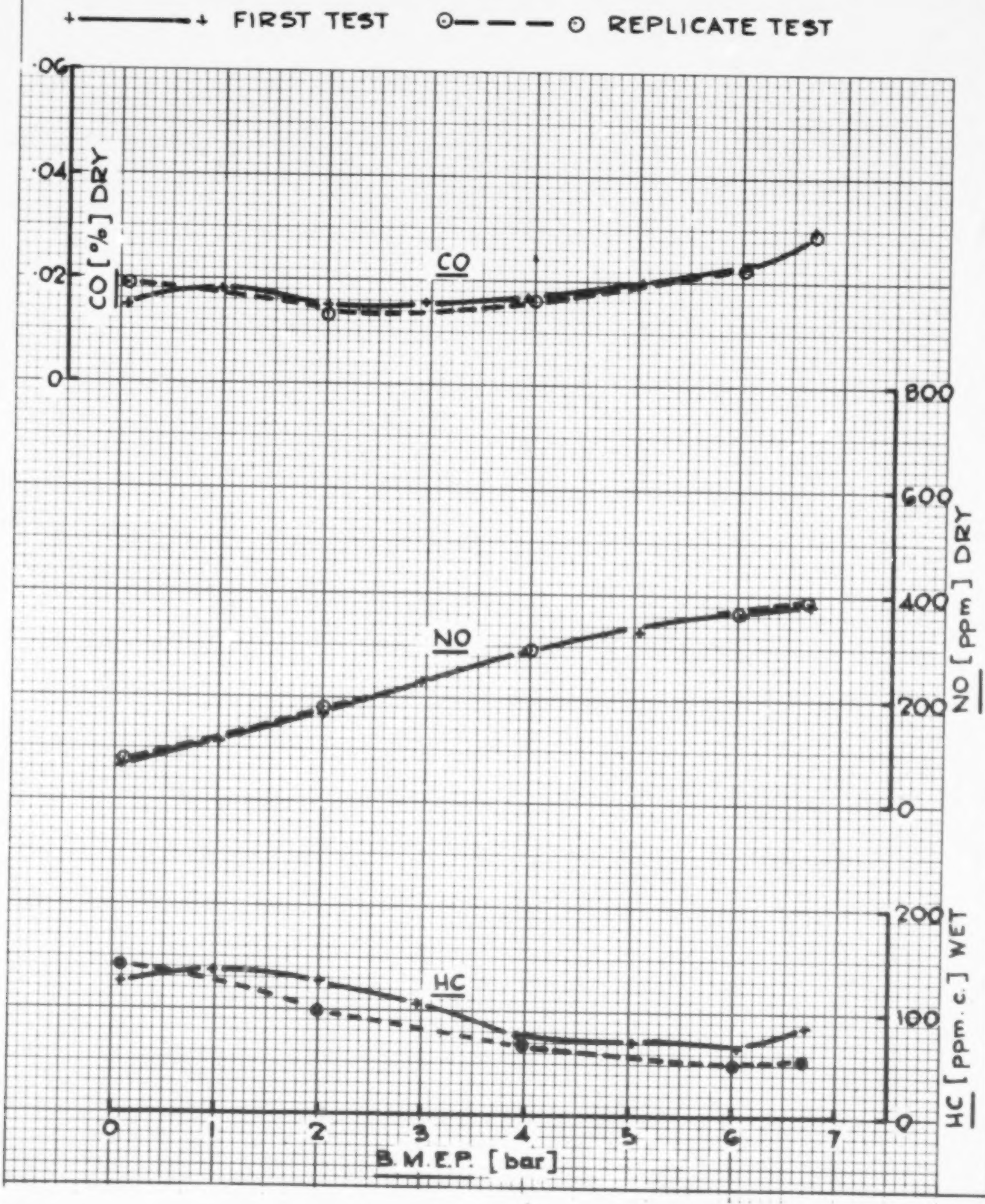


RICARDO CONSULTING ENGINEERS

FIG. No. 20
Drg. No. D34913
Date AUG. '77
Engine Curve No.7

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5 CYL.
HC, NO AND CO EMISSIONS AT 25 rev/s

STANDARD AS RECEIVED BUILD

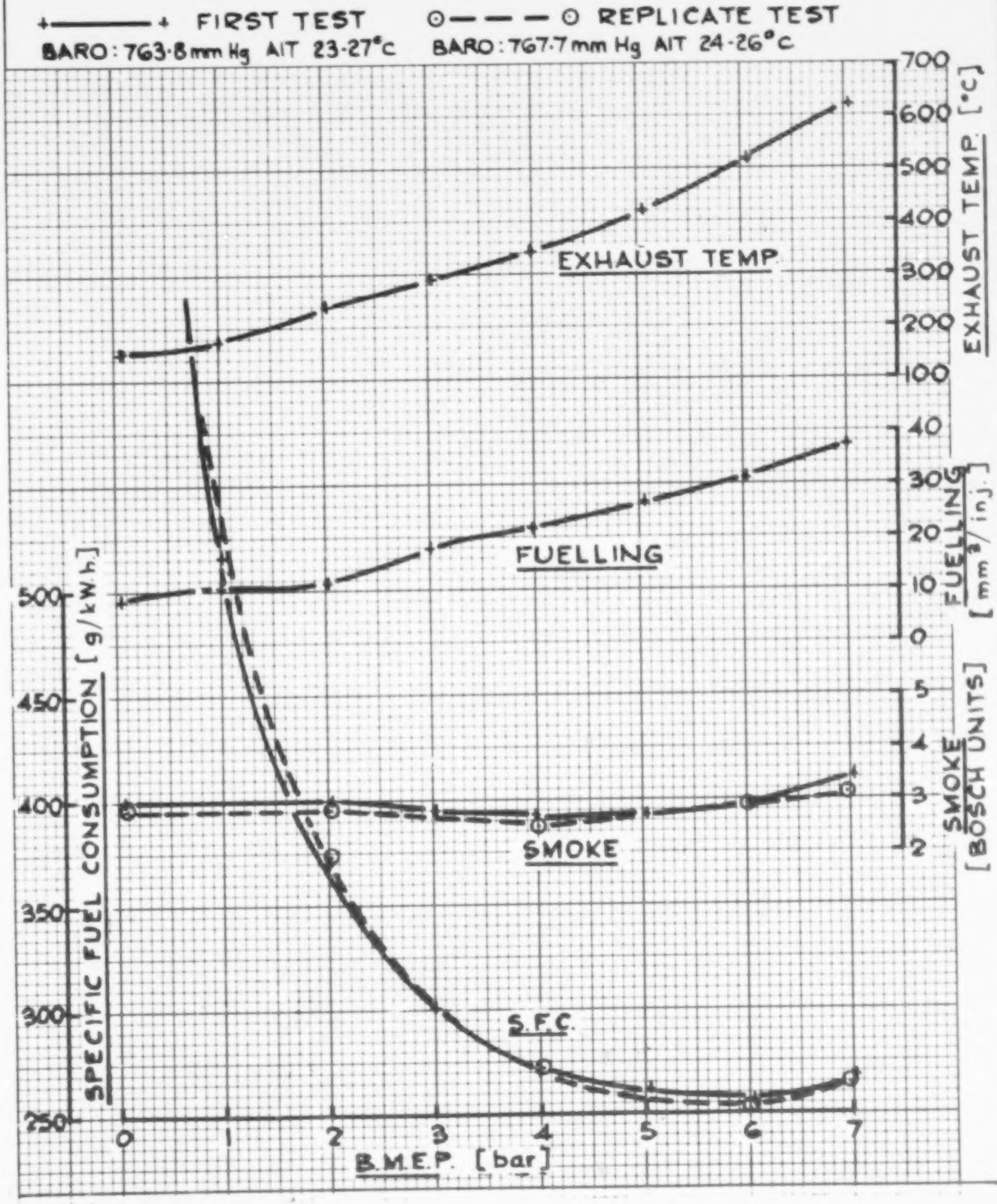


RICARDO CONSULTING ENGINEERS

FIG. No. 21
Drg. No. D34914
Date AUG.'77
Engine Curve No. 8

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92.4 mm x 5 CYL.
LOAD RANGE PERFORMANCE AT 35 rev/s

STANDARD AS RECEIVED BUILD

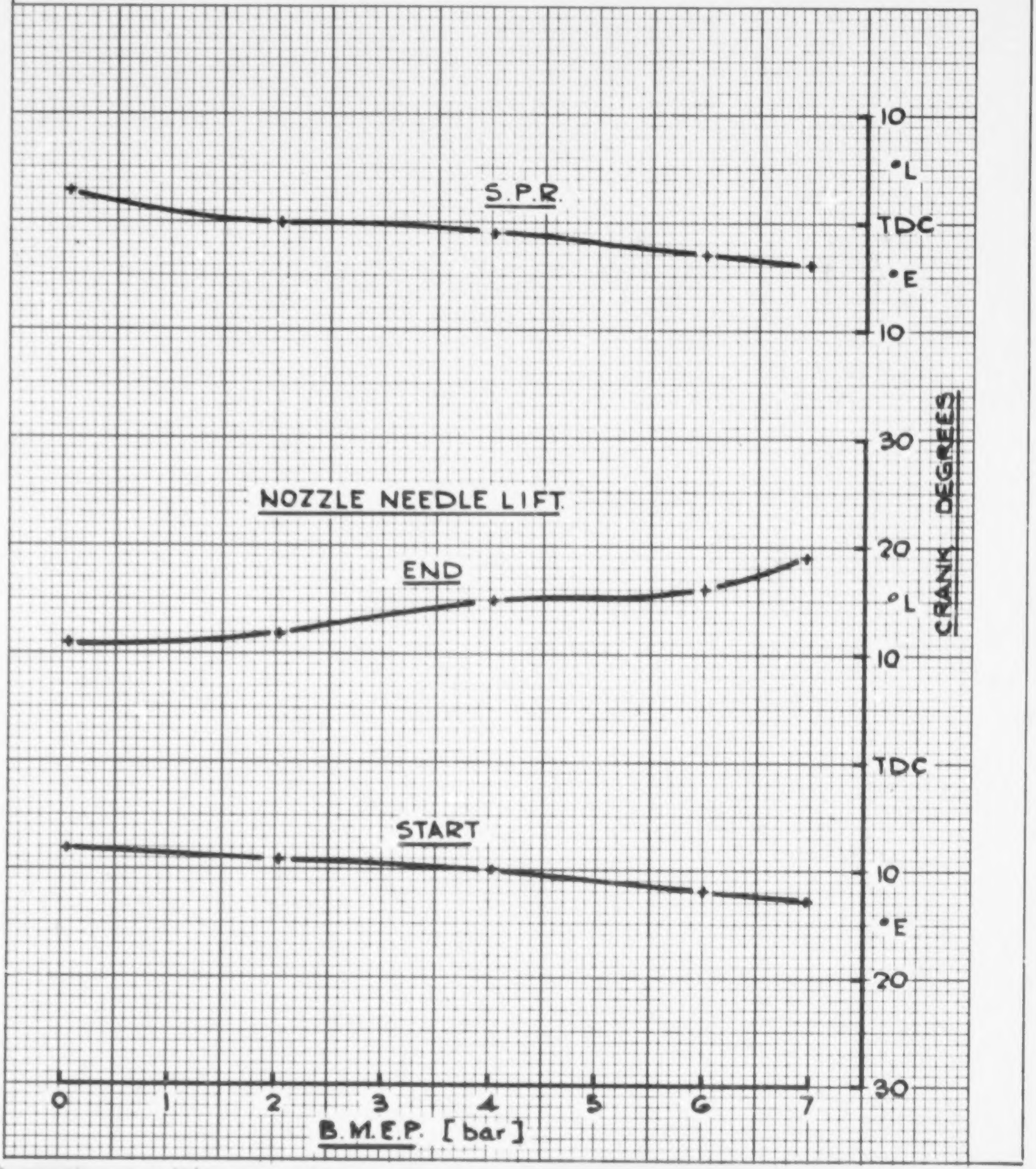


RICARDO CONSULTING ENGINEERS

FIG. No. 22
Drg. No. D34915
Date AUG. '77
Engine Curve No.9

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.
DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 35 rev/s.

STANDARD AS RECEIVED BUILD

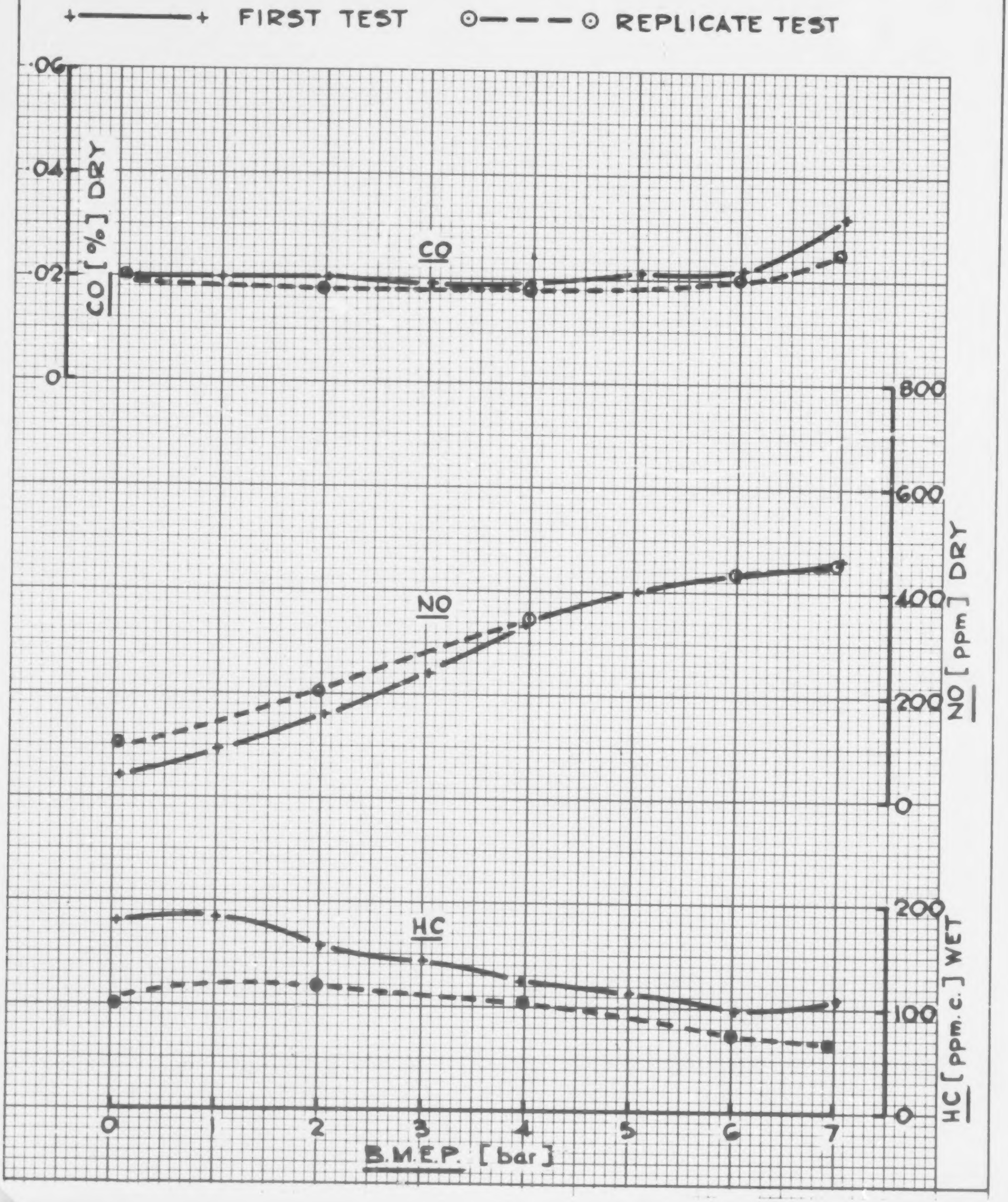


RICARDO CONSULTING ENGINEERS

FIG. No. 23
Drg. No. D34916
Date AUG. '77
Engine Curve No. 10

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.
HC, NO AND CO EMISSIONS AT 35 rev/s.

STANDARD AS RECEIVED BUILD

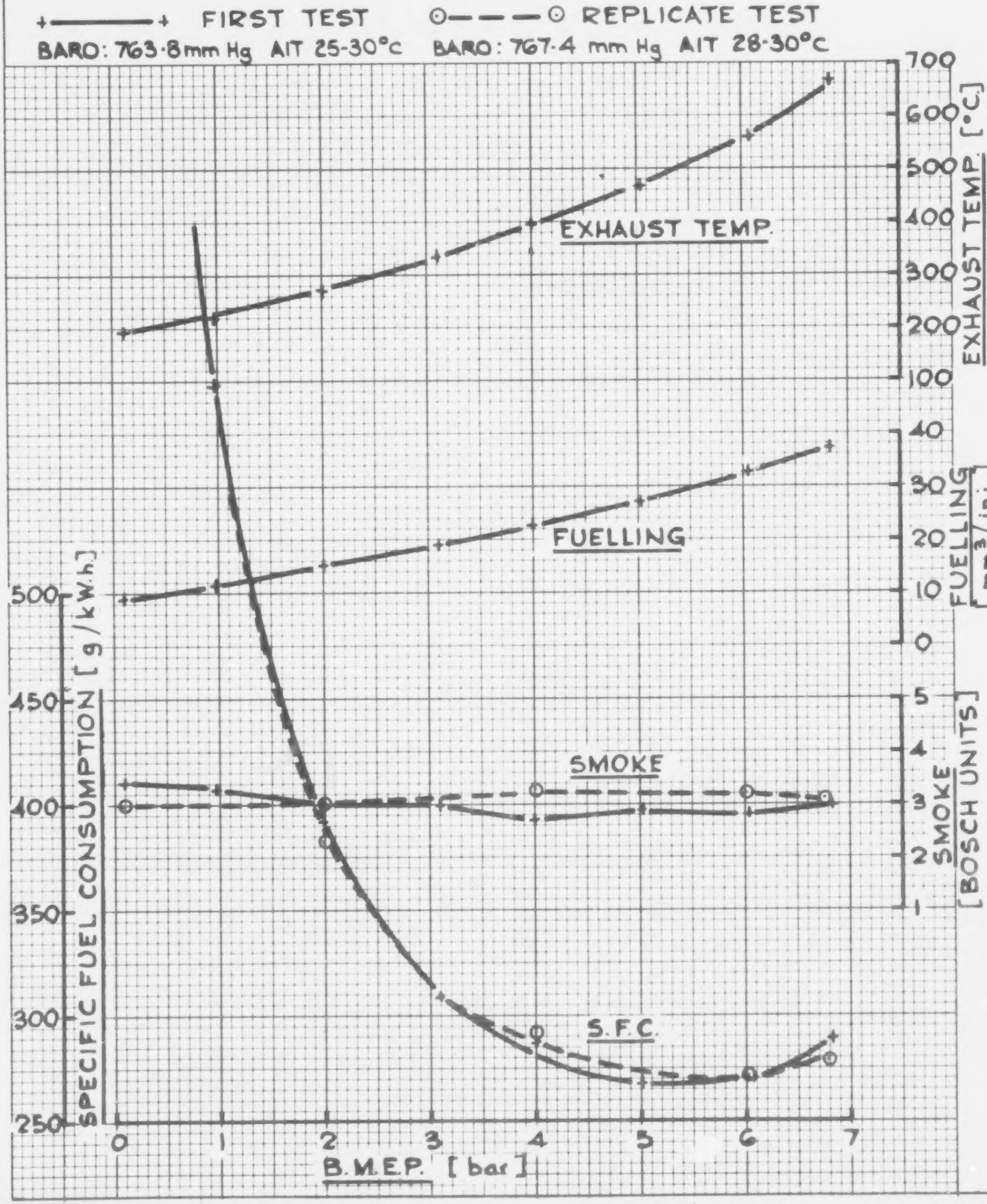


RICARDO CONSULTING ENGINEERS

FIG. No. 24
Drg. No. 034917
Date AUG. '77
Engine Curve No. 11

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5 CYL.
LOAD RANGE PERFORMANCE AT 45 rev/s.

STANDARD AS RECEIVED BUILD



RICARDO CONSULTING ENGINEERS

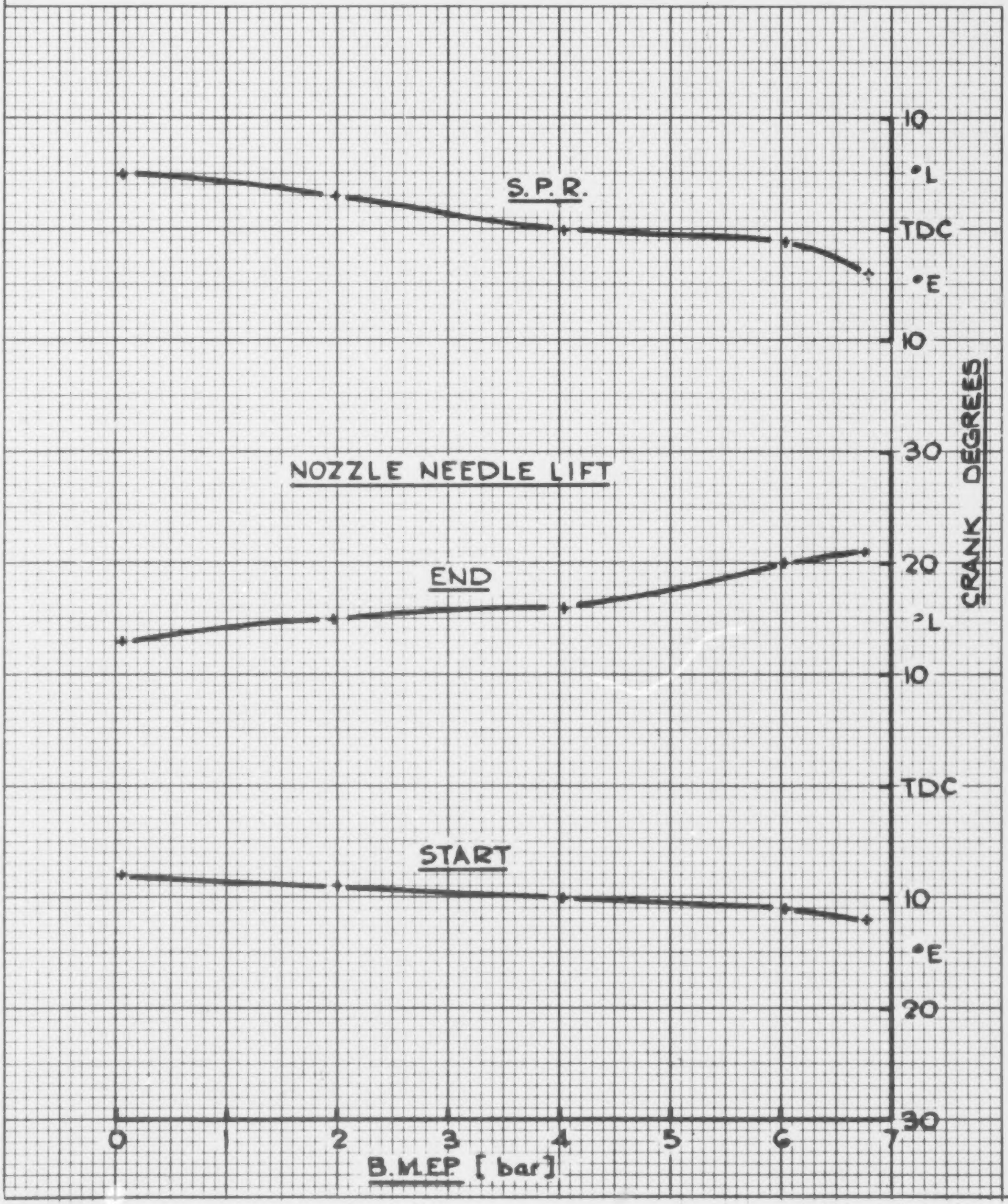
FIG. No. 25
Drg. No. D34918
Date AUG. '77
Engine Curve No. 12

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 45 rev/s.

STANDARD AS RECEIVED BUILD

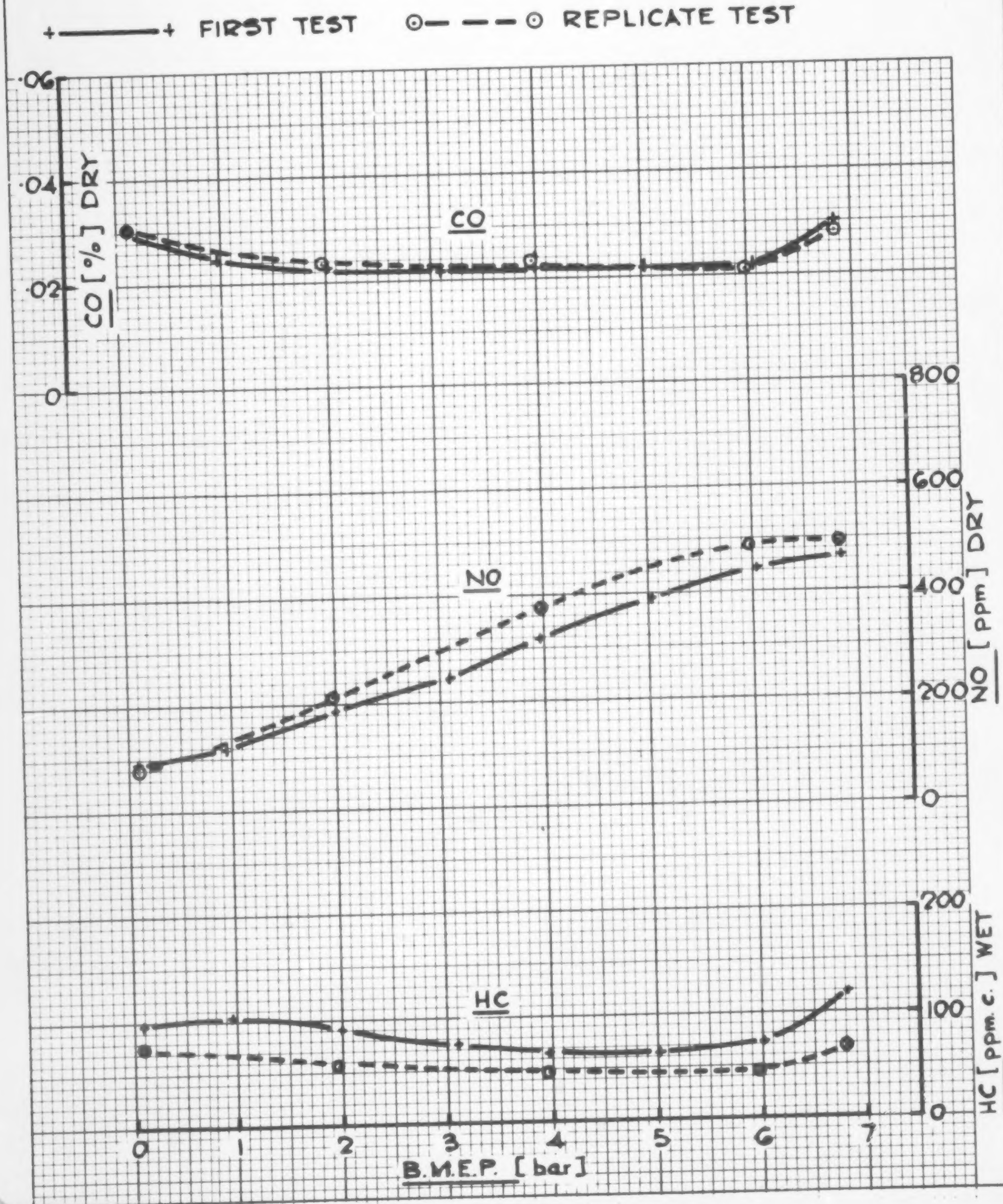


RICARDO CONSULTING ENGINEERS

FIG. No. 26
Drg. No. D34919
Date AUG. '77
Engine Curve No. 13

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5 CYL.
HC, NO AND CO EMISSIONS AT 45 rev/s.

STANDARD AS RECEIVED BUILD

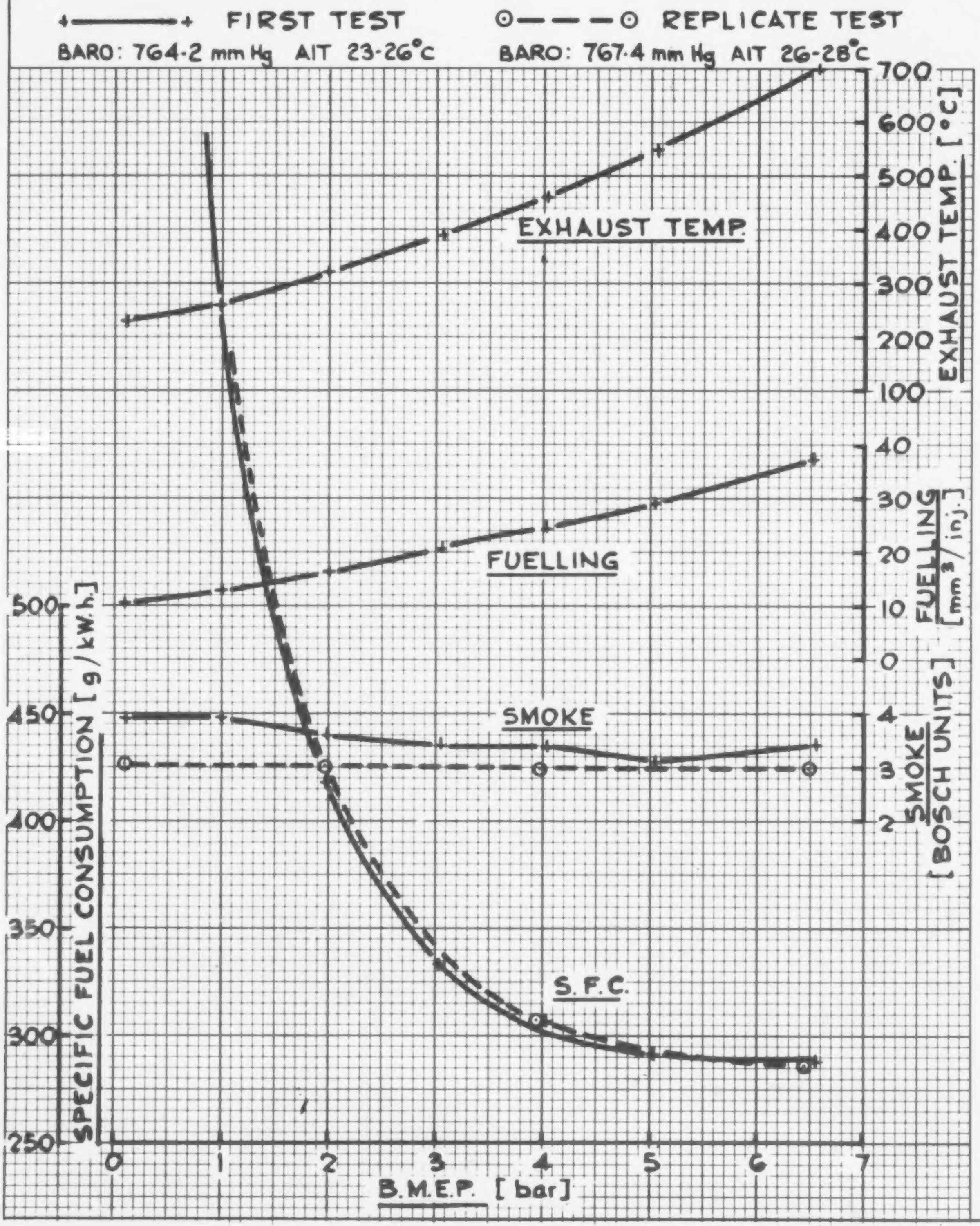


RICARDO CONSULTING ENGINEERS

FIG. No. 27
Drg. No. D34920
Date AUG. '77
Engine Curve No. 14

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5 CYL.
LOAD RANGE PERFORMANCE AT 55 rev/s.

STANDARD AS RECEIVED BUILD



RICARDO CONSULTING ENGINEERS

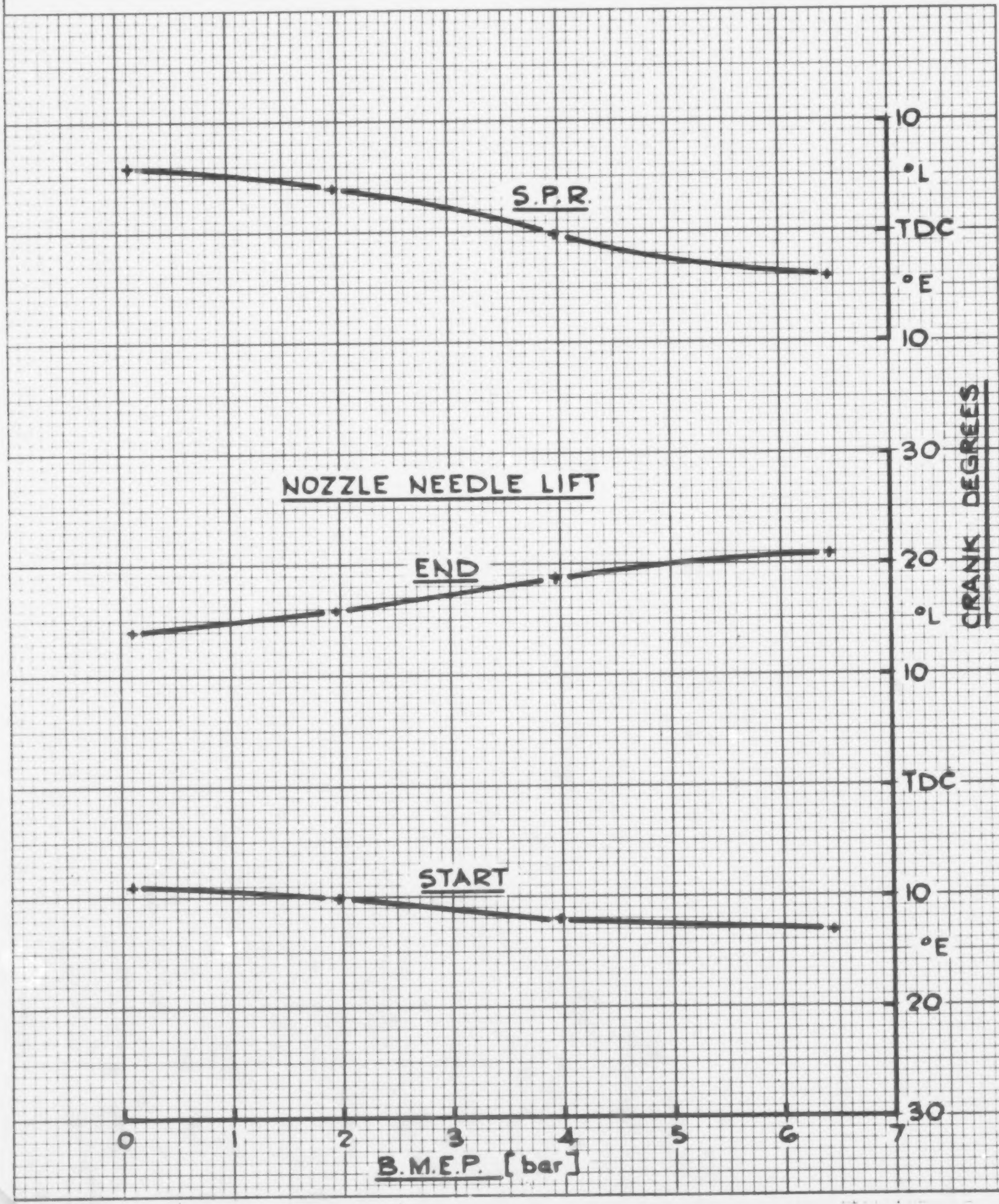
FIG. No. 28
Drg. No. D34921
Date AUG '77
Engine Curve No. 15

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.

DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 55 rev/s.

STANDARD AS RECEIVED BUILD

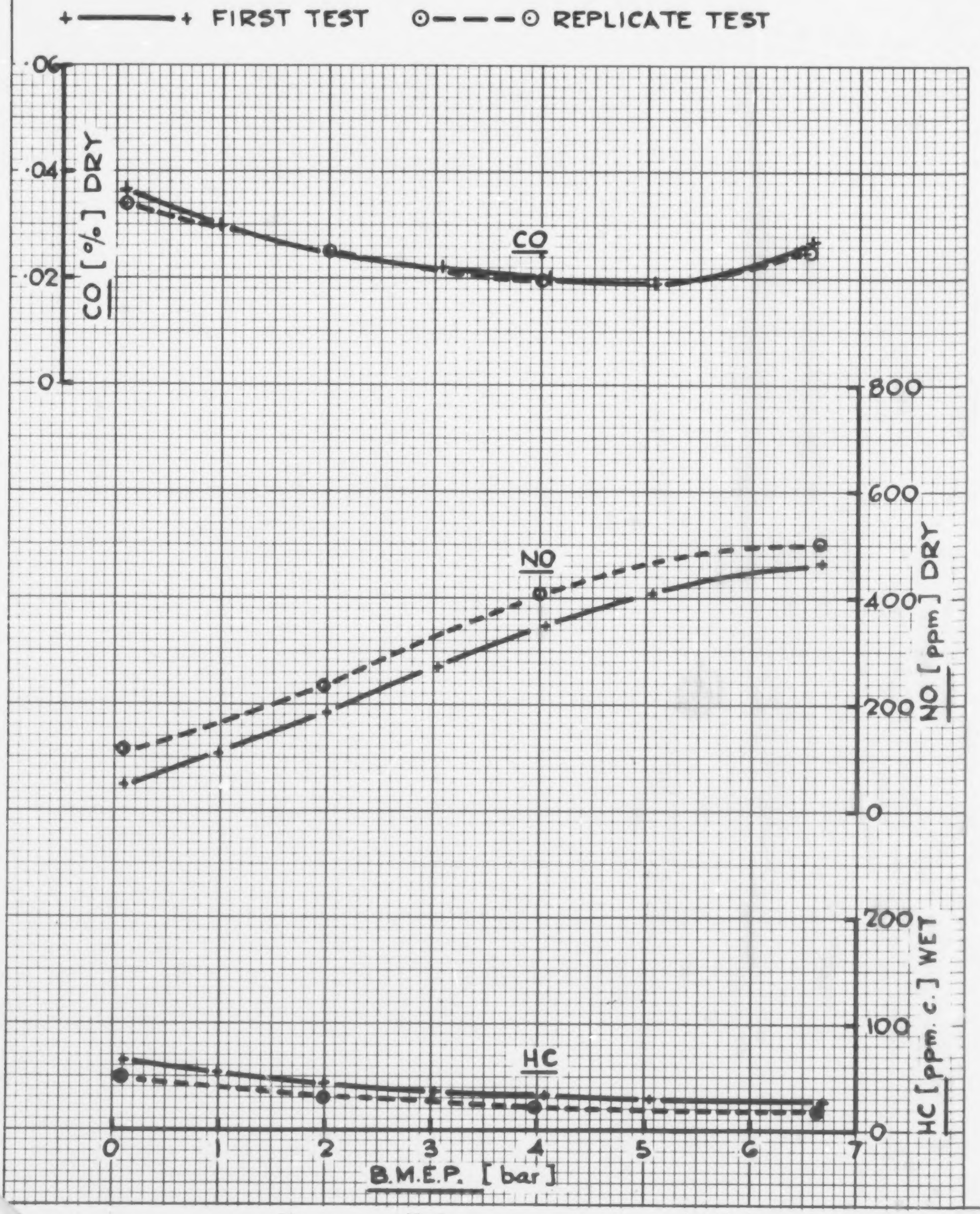


RICARDO CONSULTING ENGINEERS

FIG. No. 29
Drg. No. D34922
Date AUG. '77
Engine Curve No. 16

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92·4mm. x 5 CYL.
HC, NO AND CO EMISSIONS AT 55 rev/s.

STANDARD AS RECEIVED BUILD

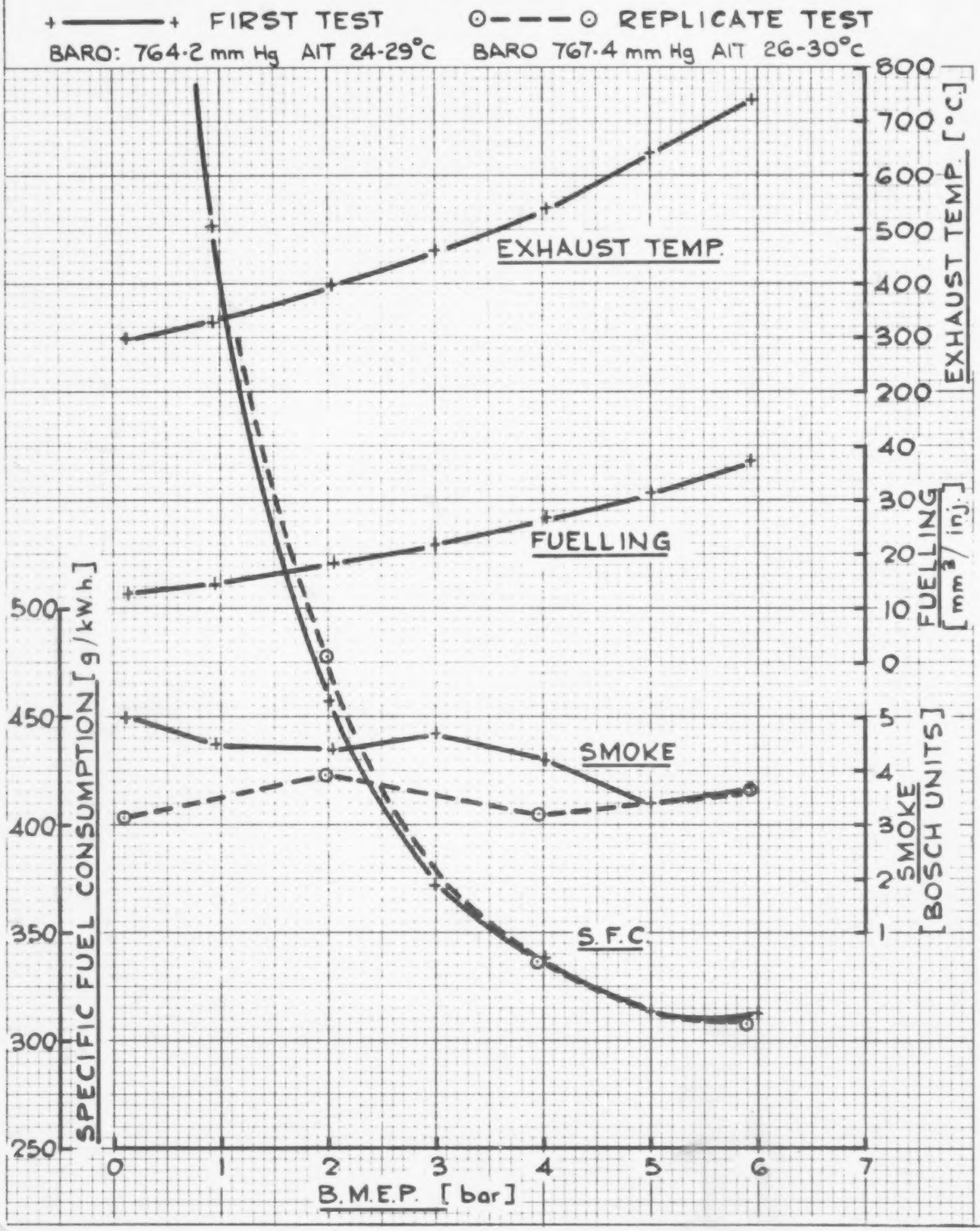


RICARDO CONSULTING ENGINEERS

FIG. No. 30
Drg. No. D34923
Date AUG. '77
Engine Curve No. 17

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
LOAD RANGE PERFORMANCE AT 65 rev/s.

STANDARD AS RECEIVED BUILD



RICARDO CONSULTING ENGINEERS

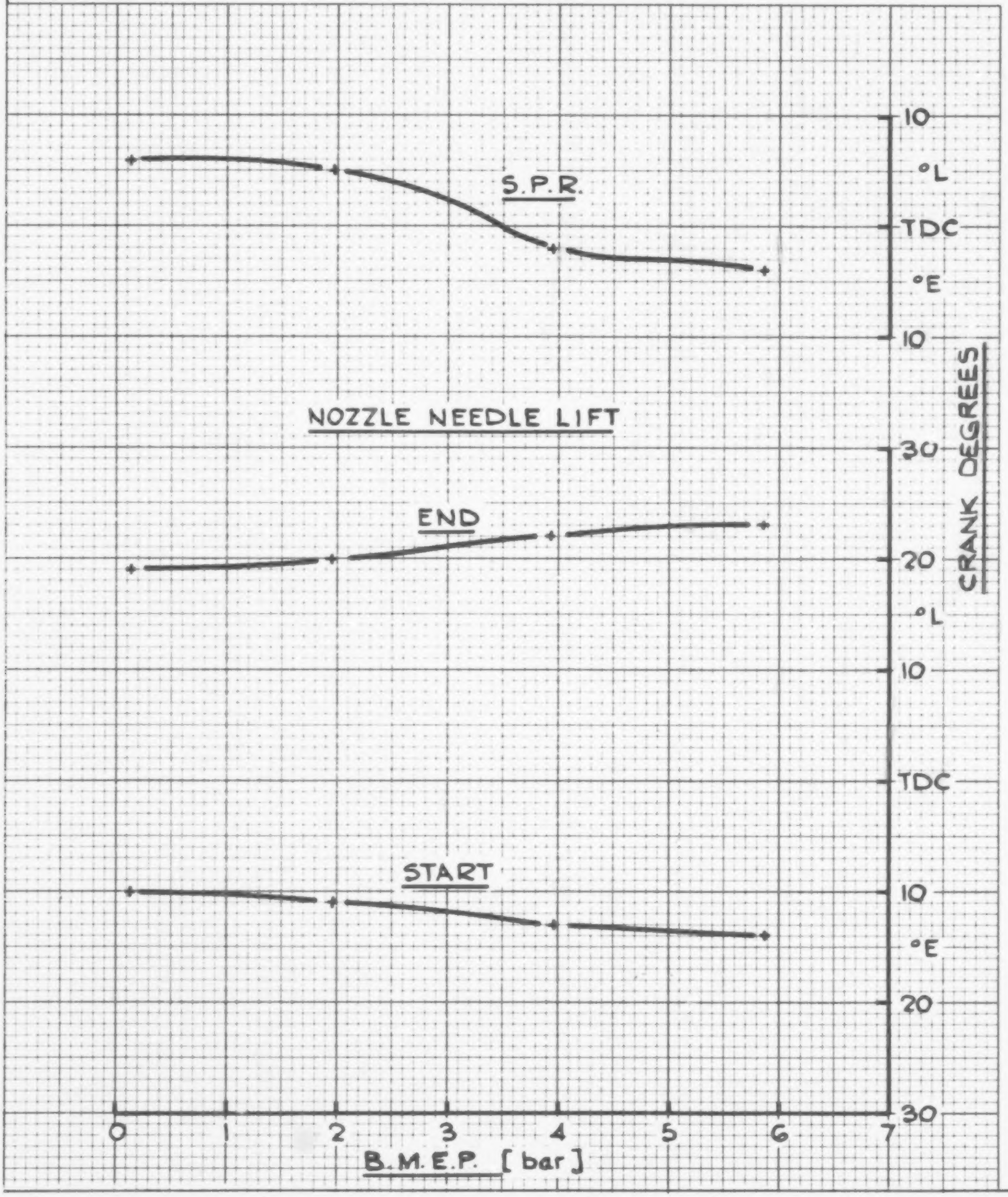
FIG. No. 31
Drg. No. D34924
Date AUG. '77
Engine Curve No. 18

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.

DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 65 rev/s.

STANDARD AS RECEIVED BUILD



RICARDO CONSULTING ENGINEERS

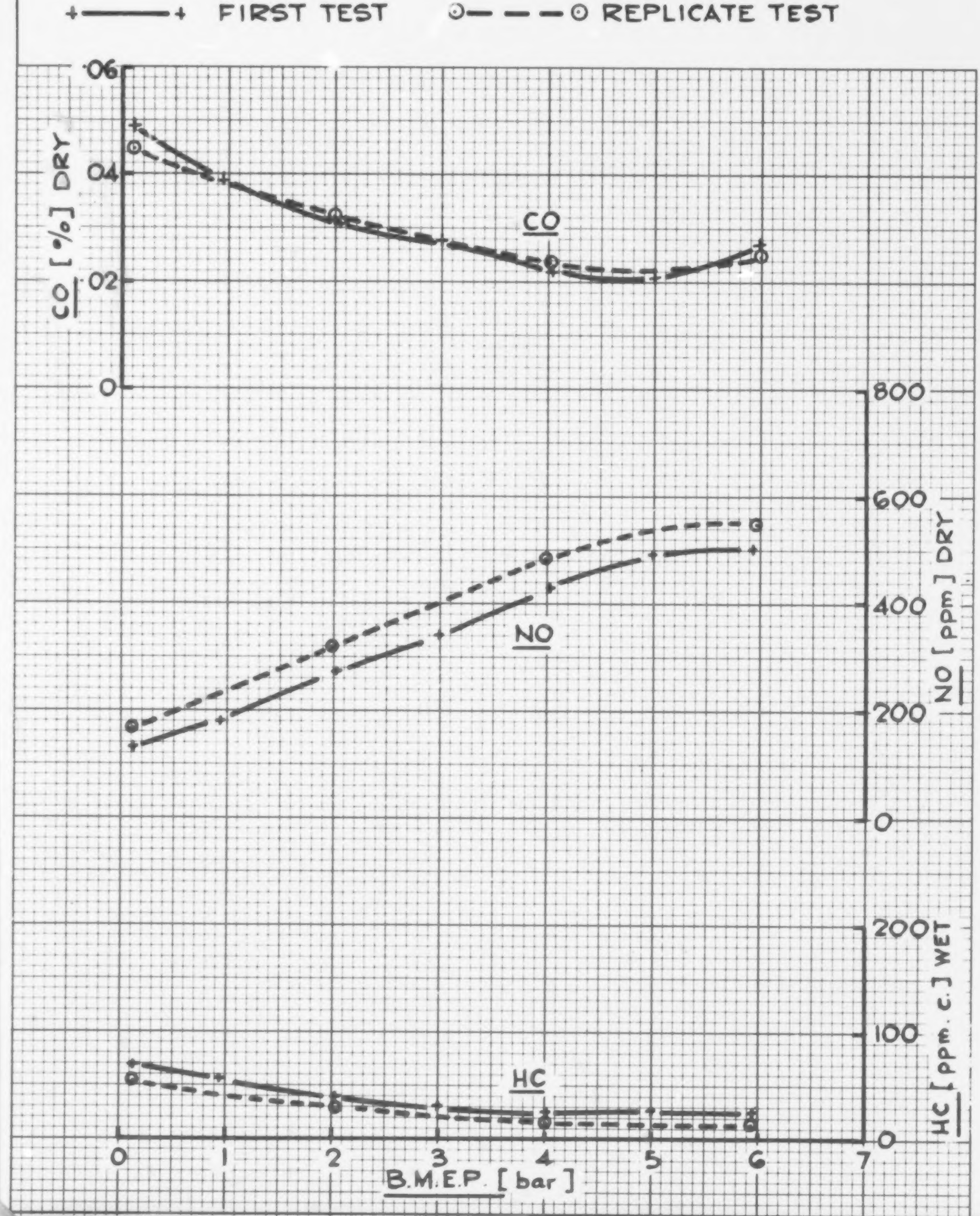
FIG. No. 32
Drg. No. D34925
Date AUG. '77
Engine Curve No. 19

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.

HC, NO AND CO EMISSIONS AT 65 rev/s.

STANDARD AS RECEIVED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 33

Drg. No. D34926

Date AUG.'77

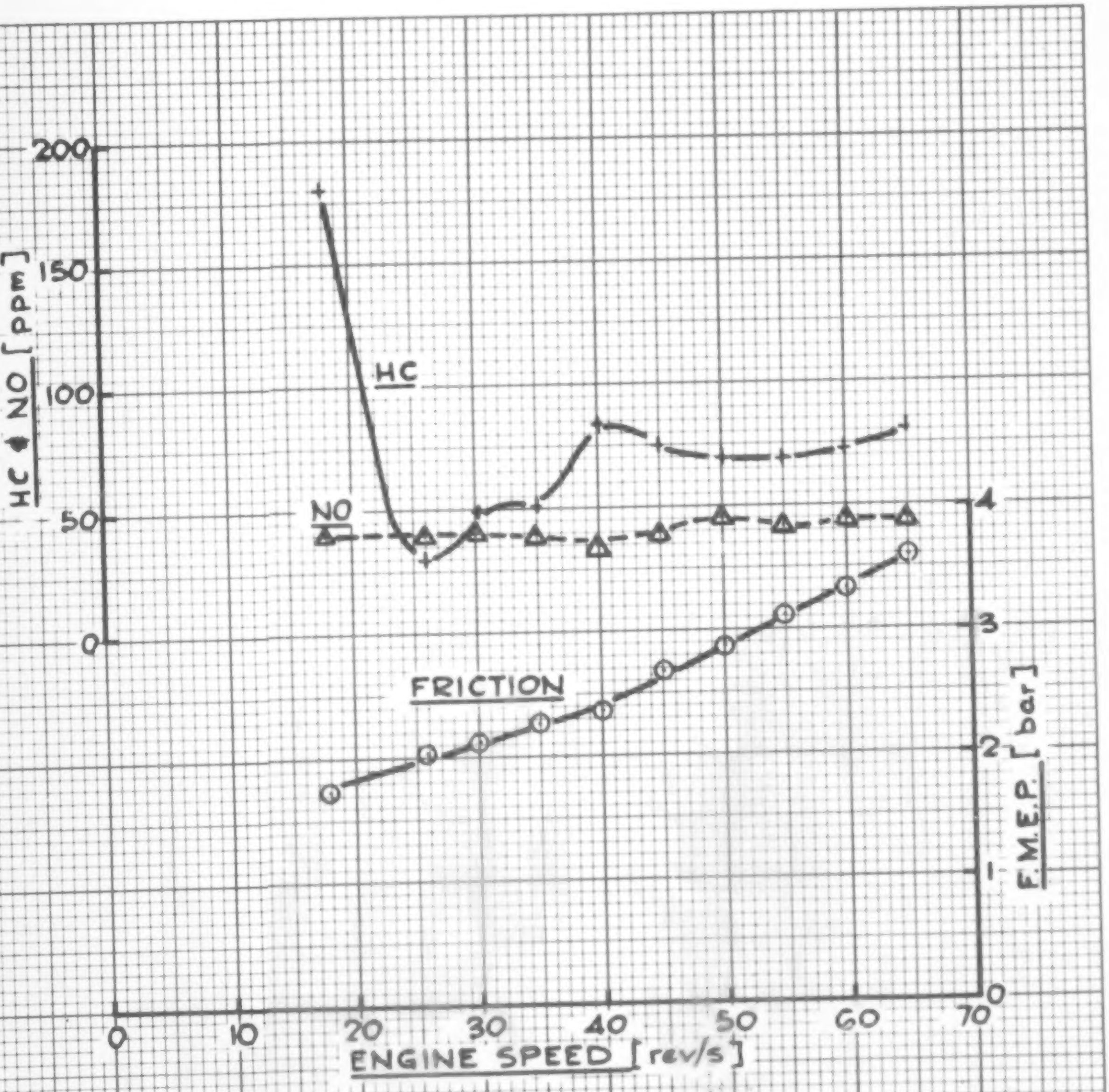
Engine Curve 26

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

MOTORING FRICTION AND EMISSIONS UNDER OVERRUN CONDITIONS.

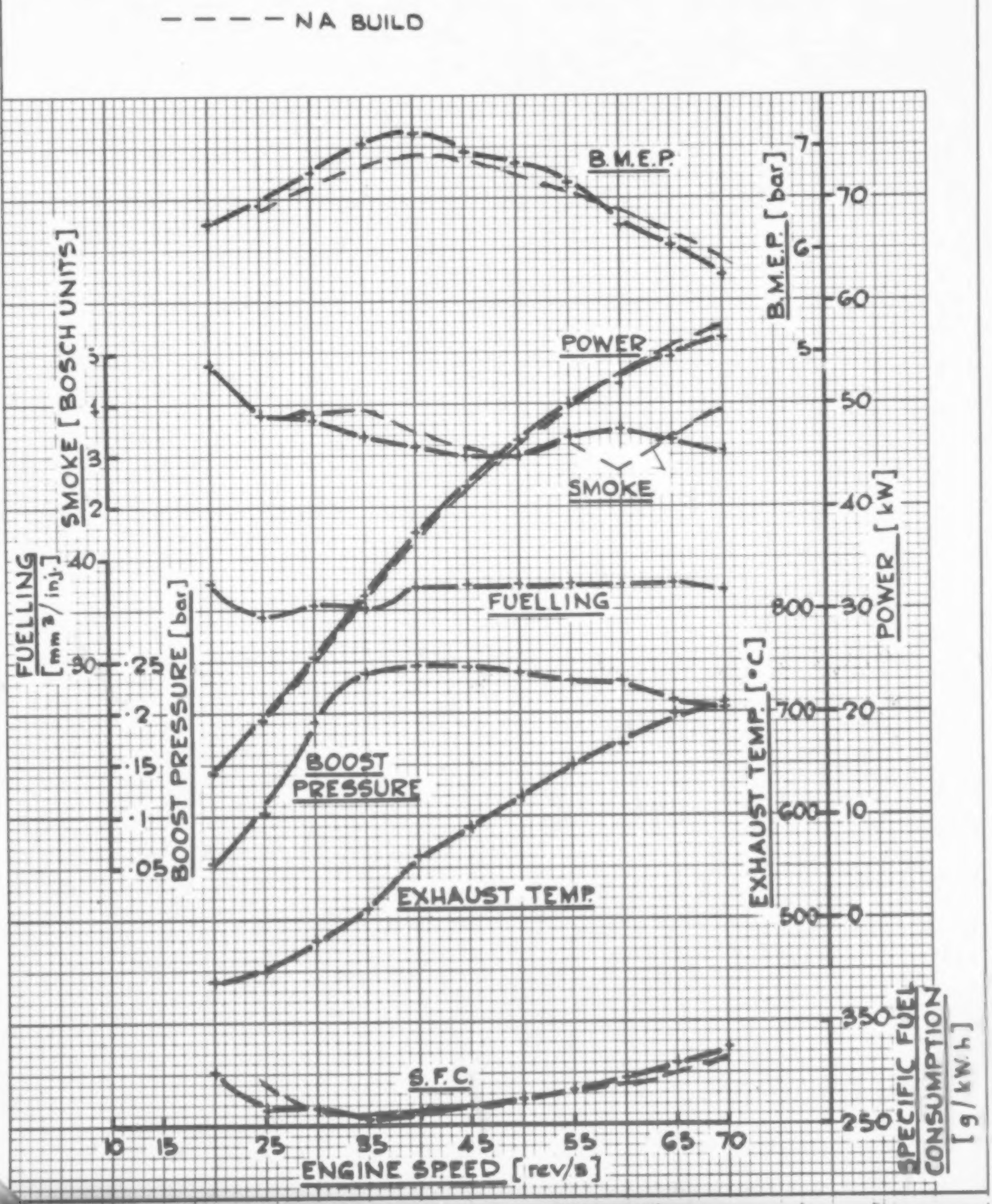
AS RECEIVED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 34
Drg. No. D34927
Date AUG.'77
Engine Curve No. 27

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm × 92.4 mm × 5 CYL.
POWER CURVE WITH TURBOCHARGER FITTED



RICARDO CONSULTING ENGINEERS

FIG. No. 35
Drg. No. D34928
Date AUG.'77
Engine Curve No. 28

EPA MODULATED EGR STUDY

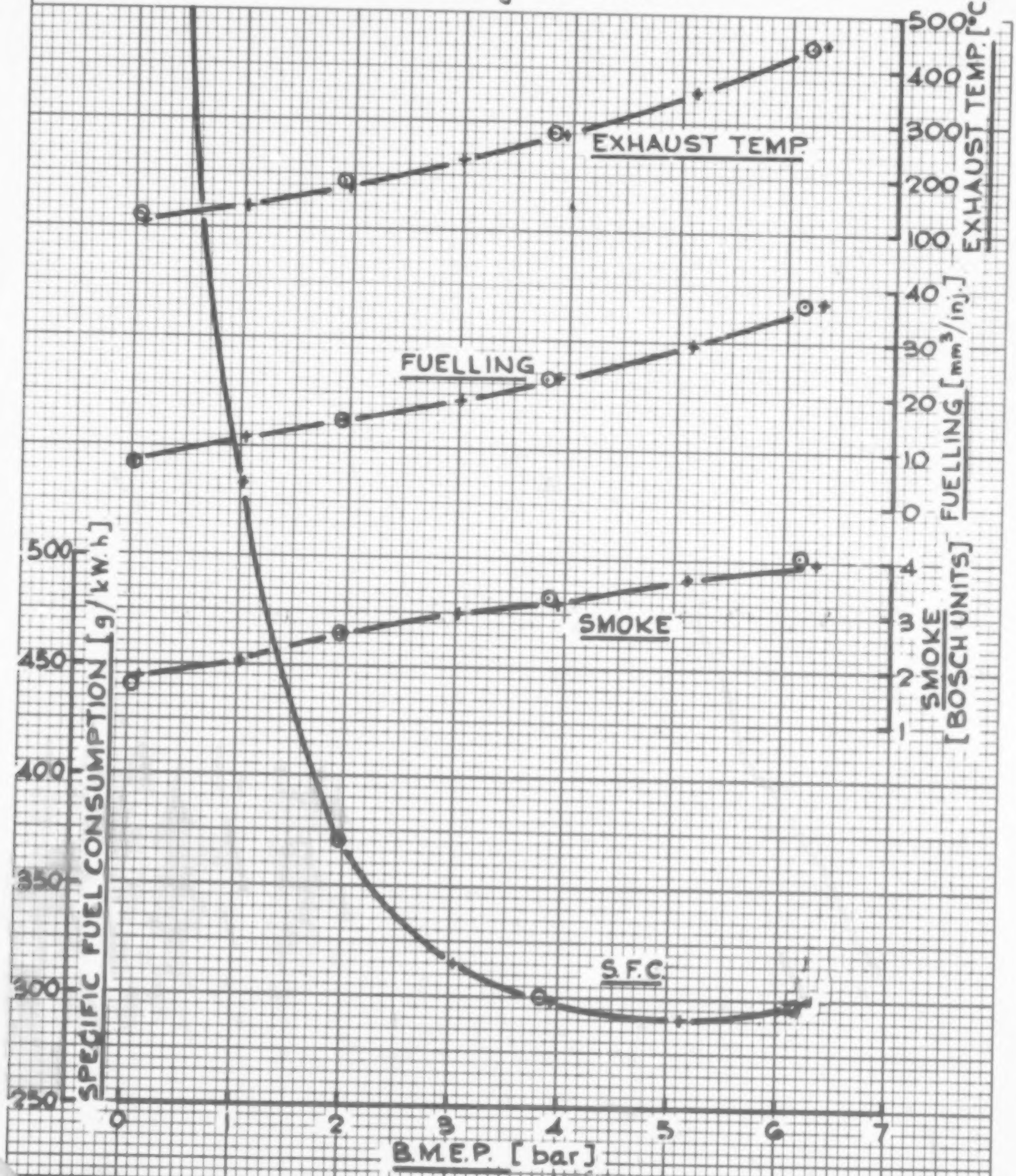
MERCEDES OM617 ENGINE 91 mm x 92.4 mm. x 5 CYL.

LOAD RANGE PERFORMANCE AT 15 rev/s

TURBOCHARGED BUILD

+———+ FIRST TEST ⊙— — —⊙ REPLICATE TEST

BARO: 762.5 mm Hg AIT 22-26°C



RICARDO CONSULTING ENGINEERS

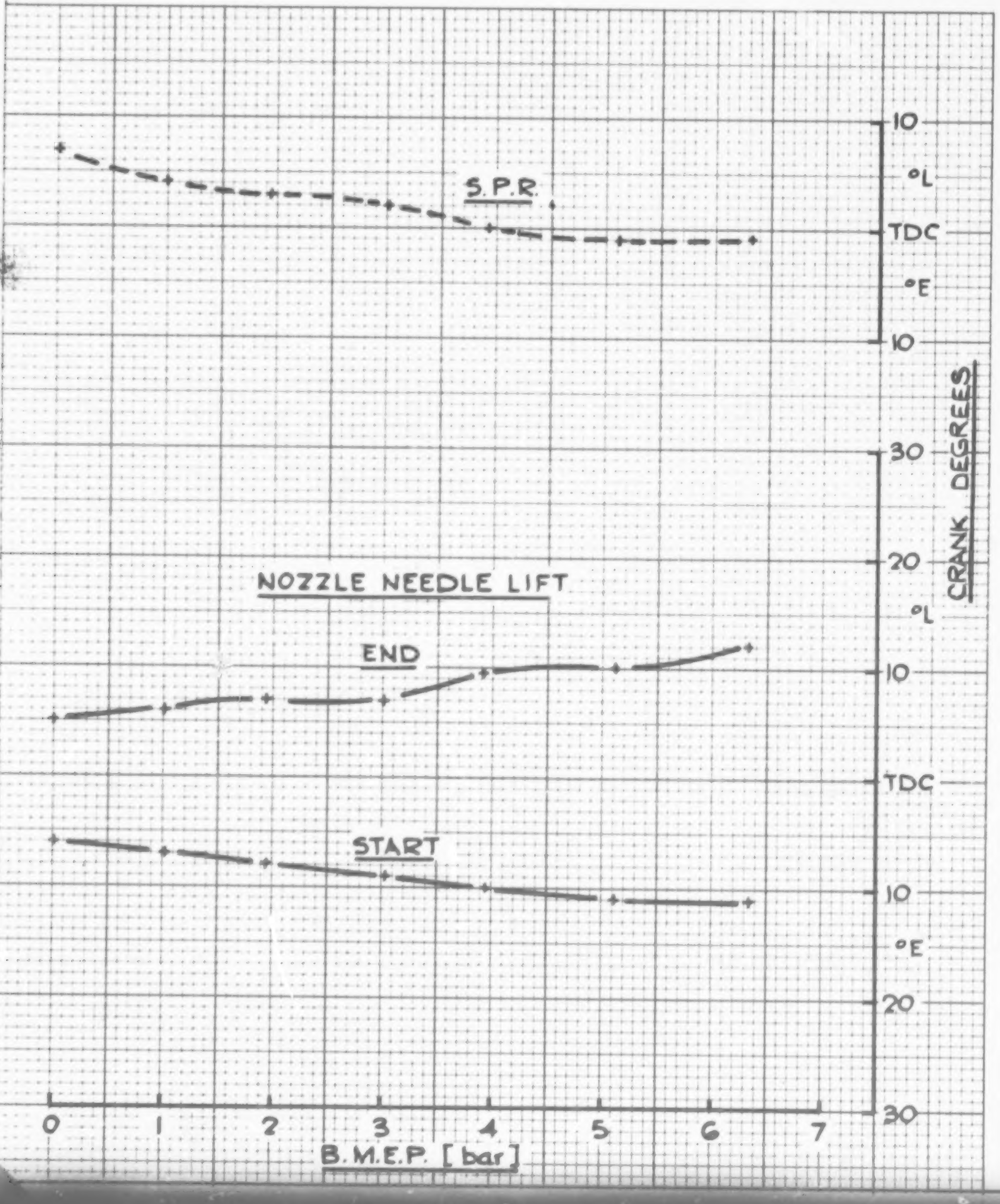
FIG. No. 36
Drg. No. D34929
Date AUG.'77
Engine Curve No. 28A

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm × 92·4 mm × 5 CYL.

DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 15 rev/s.

TURBOCHARGED BUILD

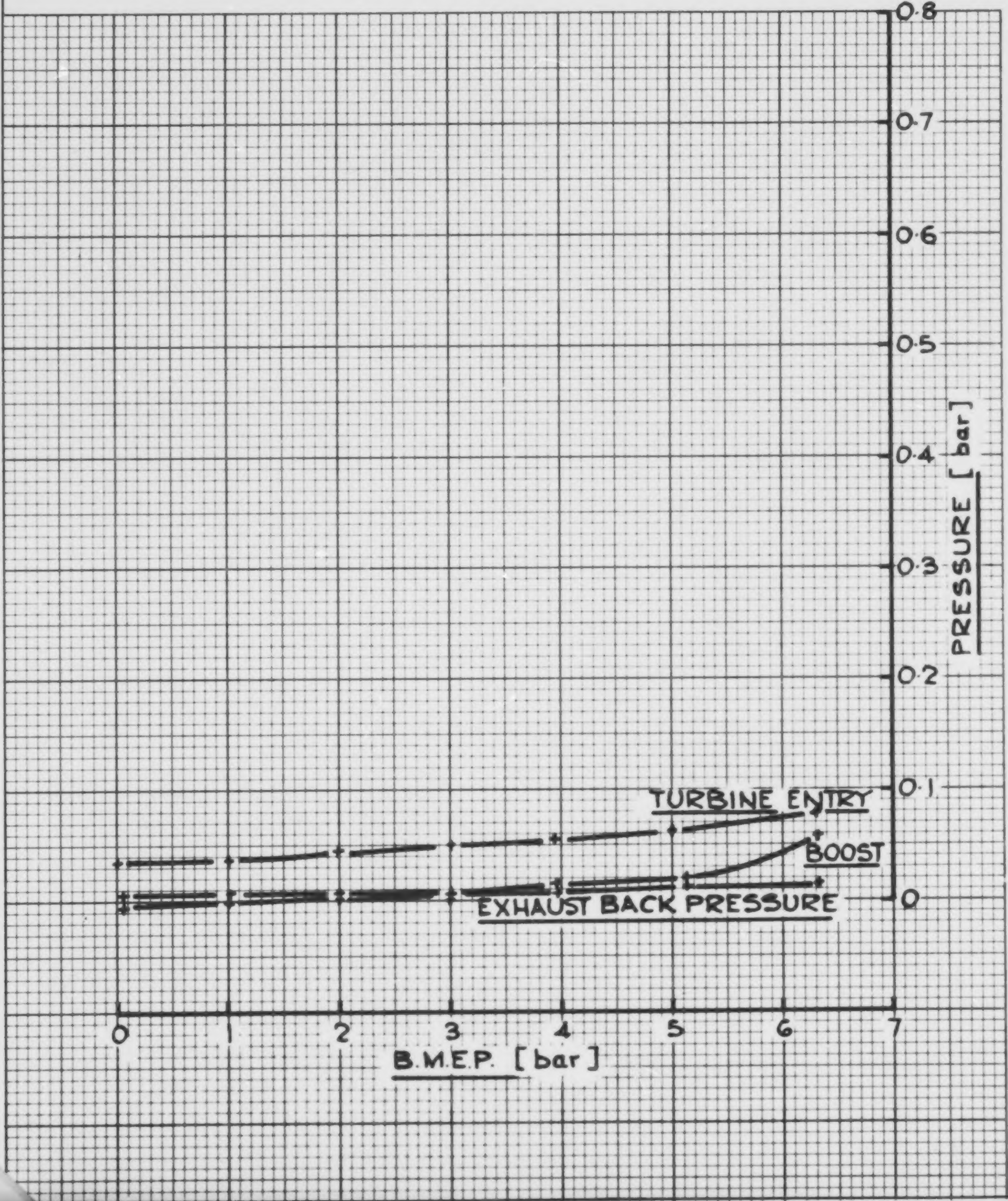


RICARDO CONSULTING ENGINEERS

FIG. No. 37
Drg. No. D34930
Date AUG. '77
Engine Curve No. 30

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
TURBOCHARGER PERFORMANCE AT 15 rev/s

TURBOCHARGED BUILD



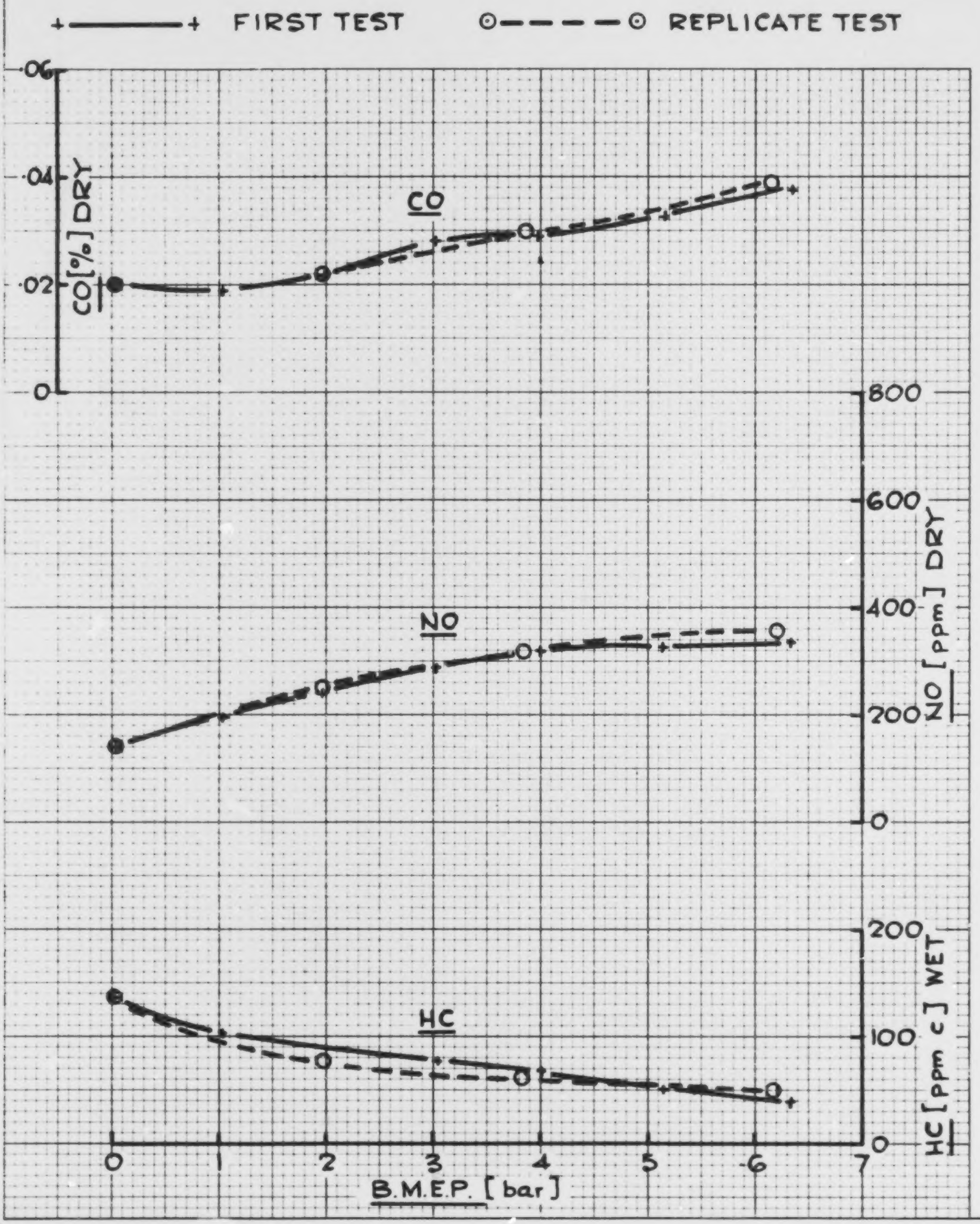
RICARDO CONSULTING ENGINEERS

FIG. No. 38
Drg. No. D34931
Date AUG. '77
Engine Curve No. 29

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm × 92.4 mm × 5 CYL.
HC, CO AND NO EMISSIONS AT 15 rev/s

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

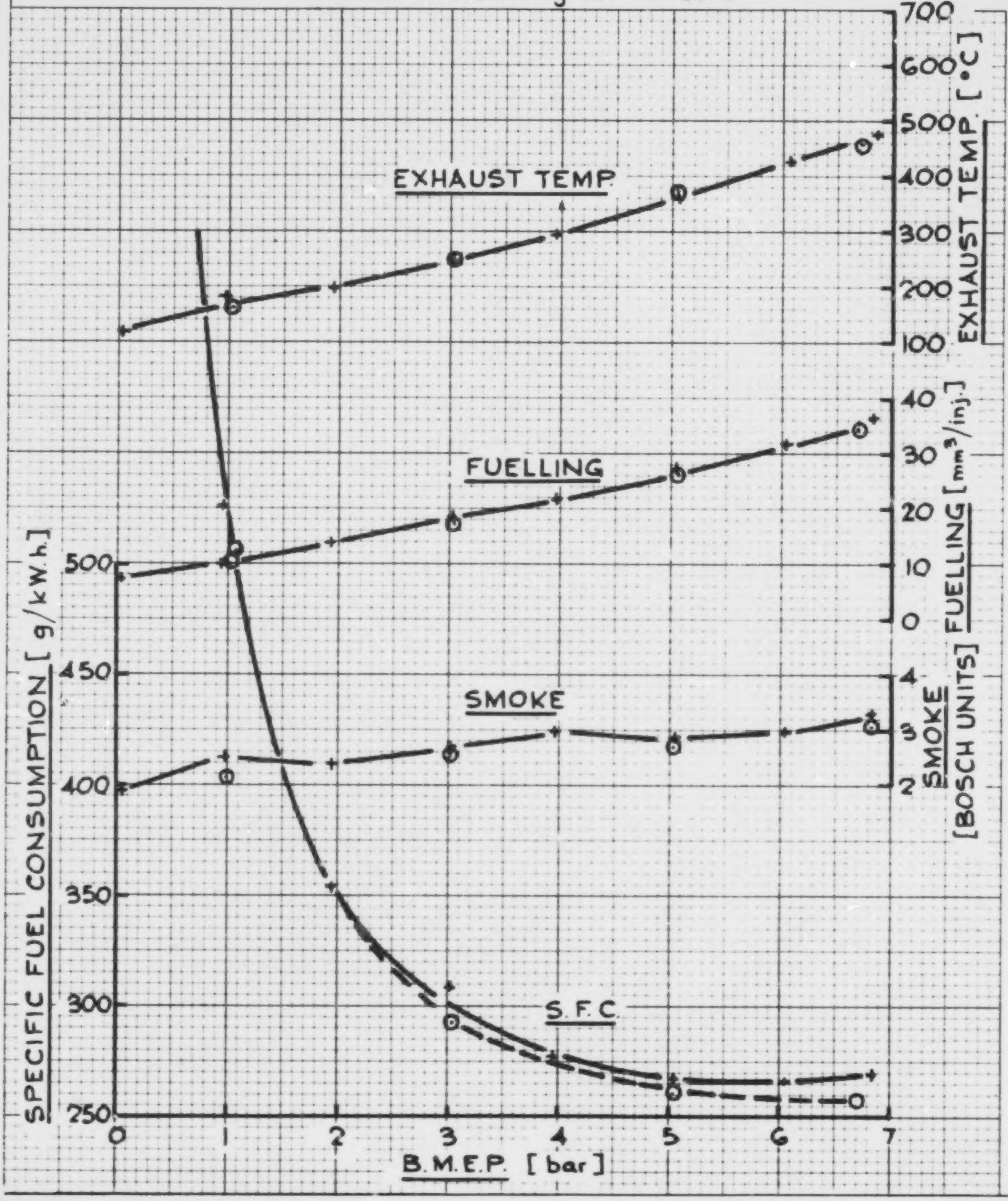
FIG. No. 39
Drg. No. D34932
Date AUG. '77
Engine Curve No. 31

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
LOAD RANGE PERFORMANCE AT 25 rev/s

TURBOCHARGED BUILD

+——————+ FIRST TEST   ʘ– – – –ʘ REPLICATE TEST

BARO: 762·3 mm Hg AIT 19 - 20°C



RICARDO CONSULTING ENGINEERS

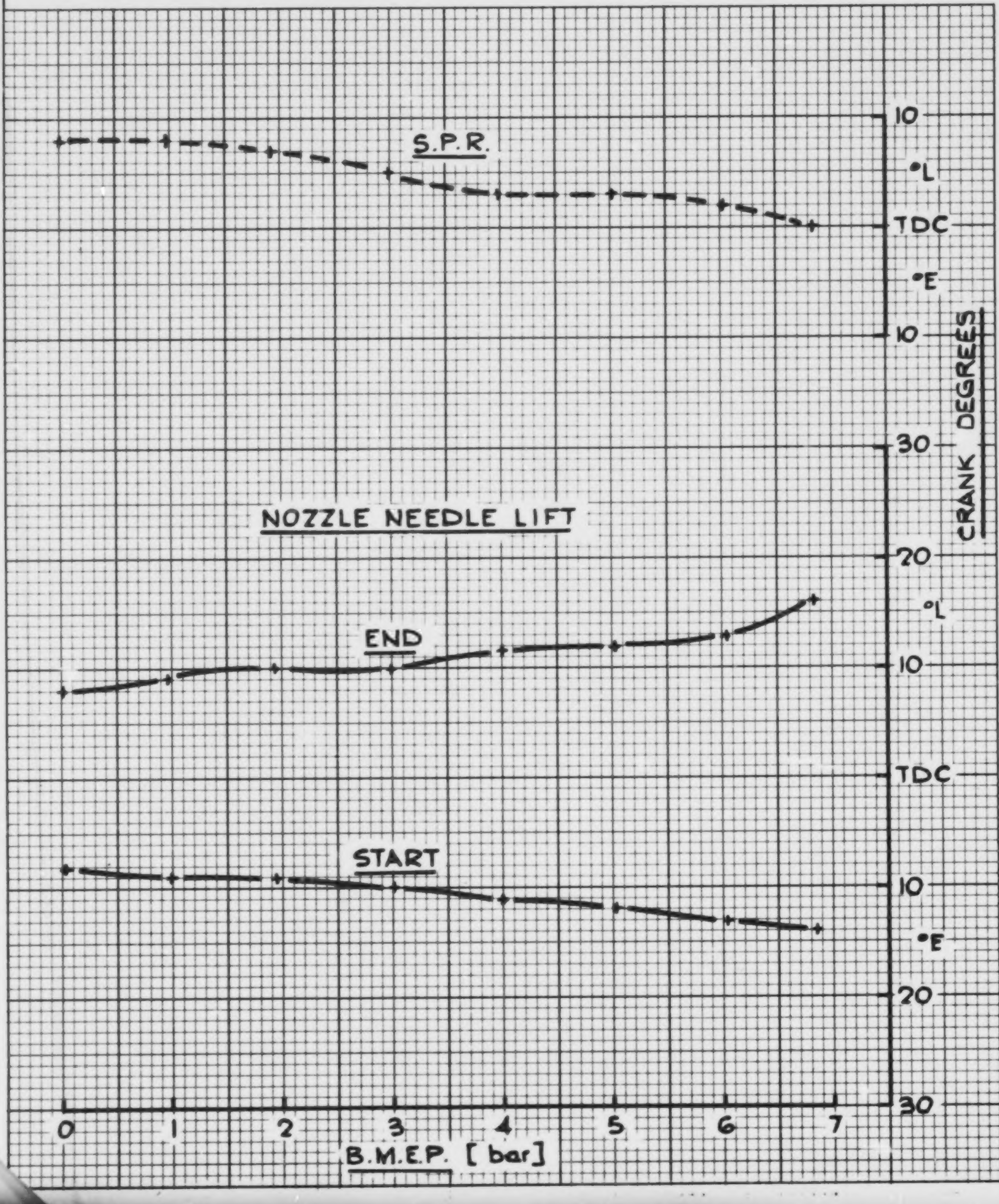
FIG. No. 40
Drg. No. D34933
Date AUG.'77
Engine Curve No. 31a

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.

DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 25 rev/s.

TURBOCHARGED BUILD

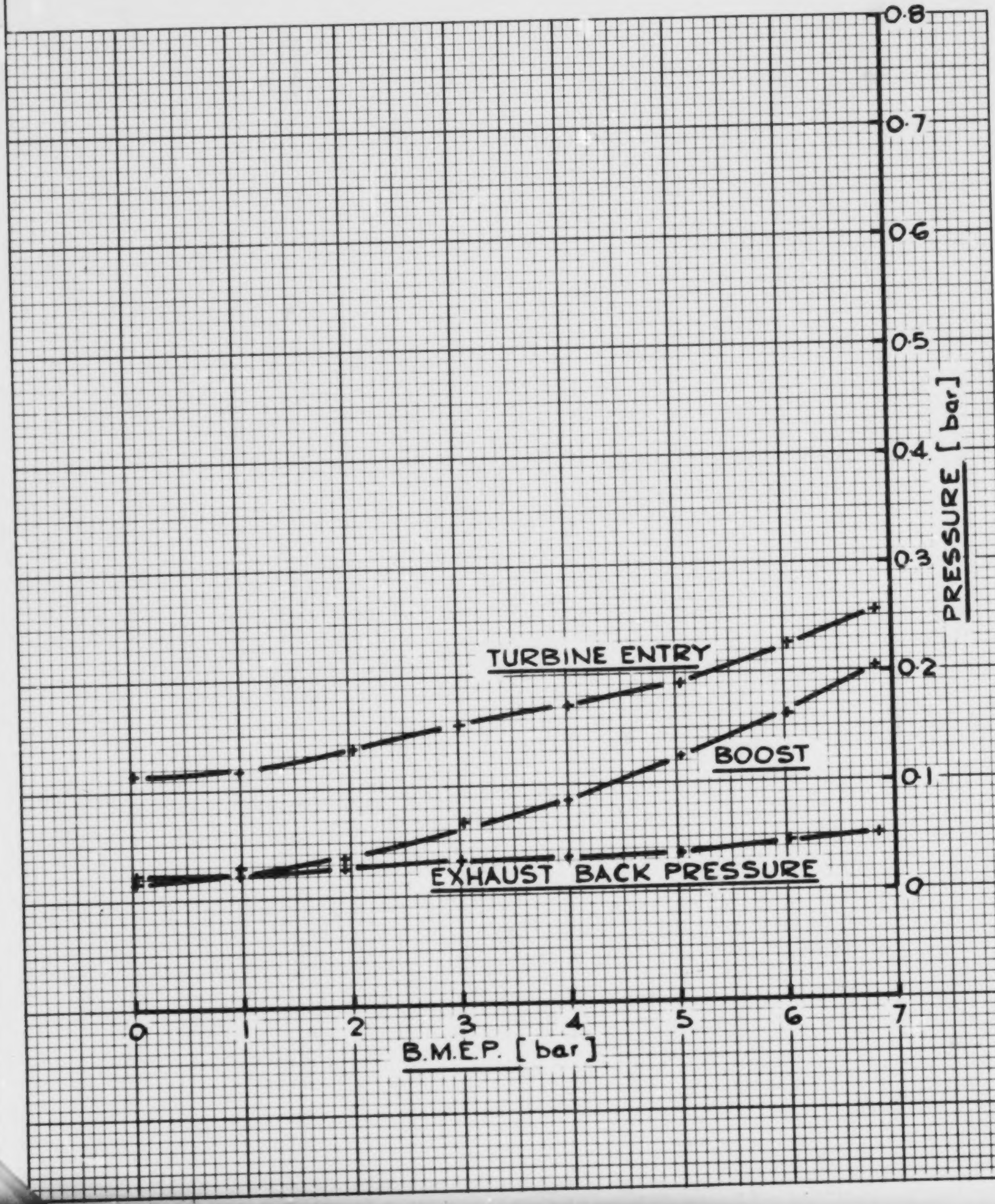


RICARDO CONSULTING ENGINEERS

FIG. No. 41
Drg. No. D34934
Date AUG. '77
Engine Curve No. 33

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm × 92·4 mm × 5 CYL.
TURBOCHARGER PERFORMANCE AT 25 rev/s.

TURBOCHARGED BUILD

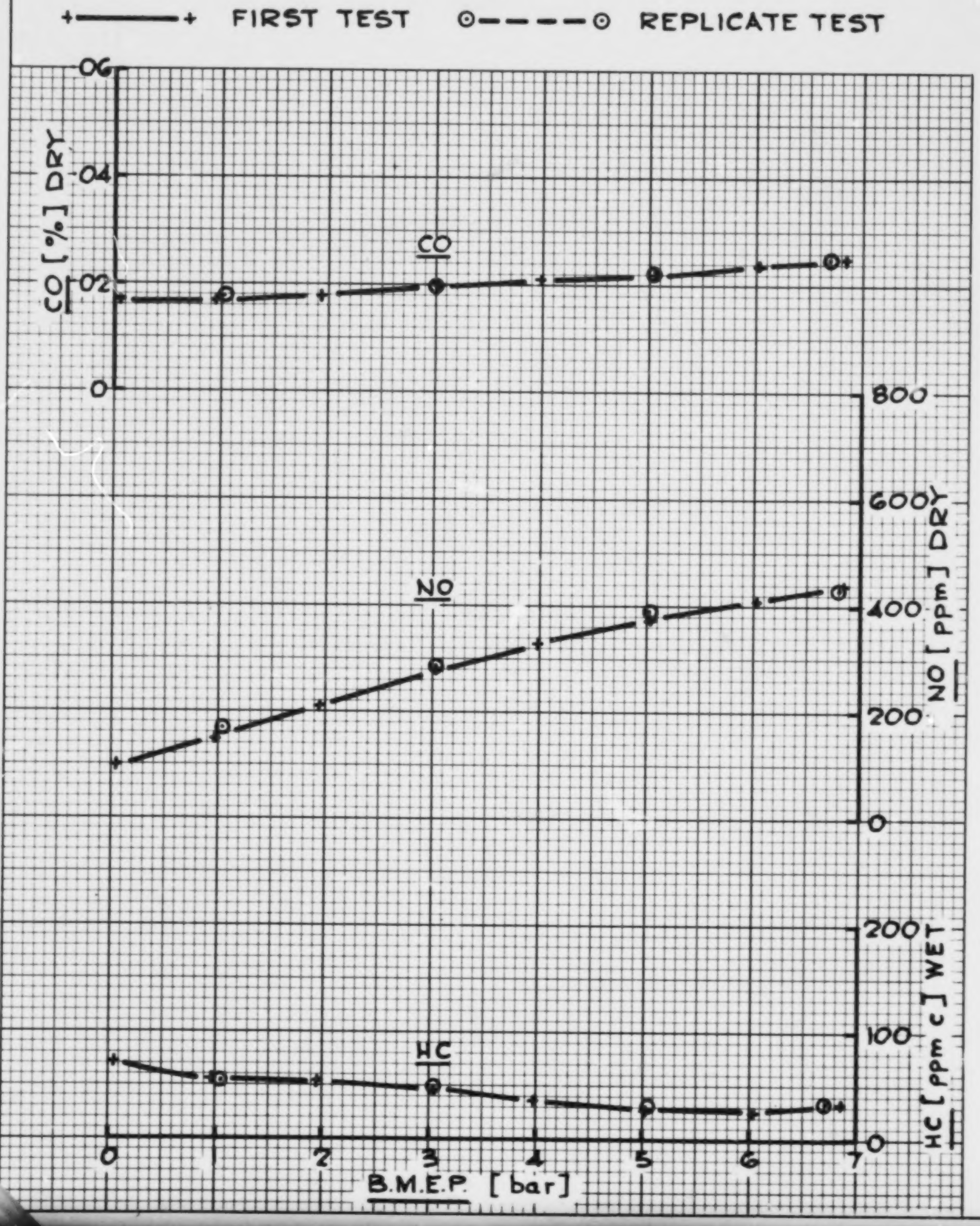


RICARDO CONSULTING ENGINEERS

FIG. No. 42
Drg. No. D34935
Date AUG. 77
Engine Curve No. 32

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5 CYL.
HC, CO AND NO EMISSIONS AT 25 rev/s.

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

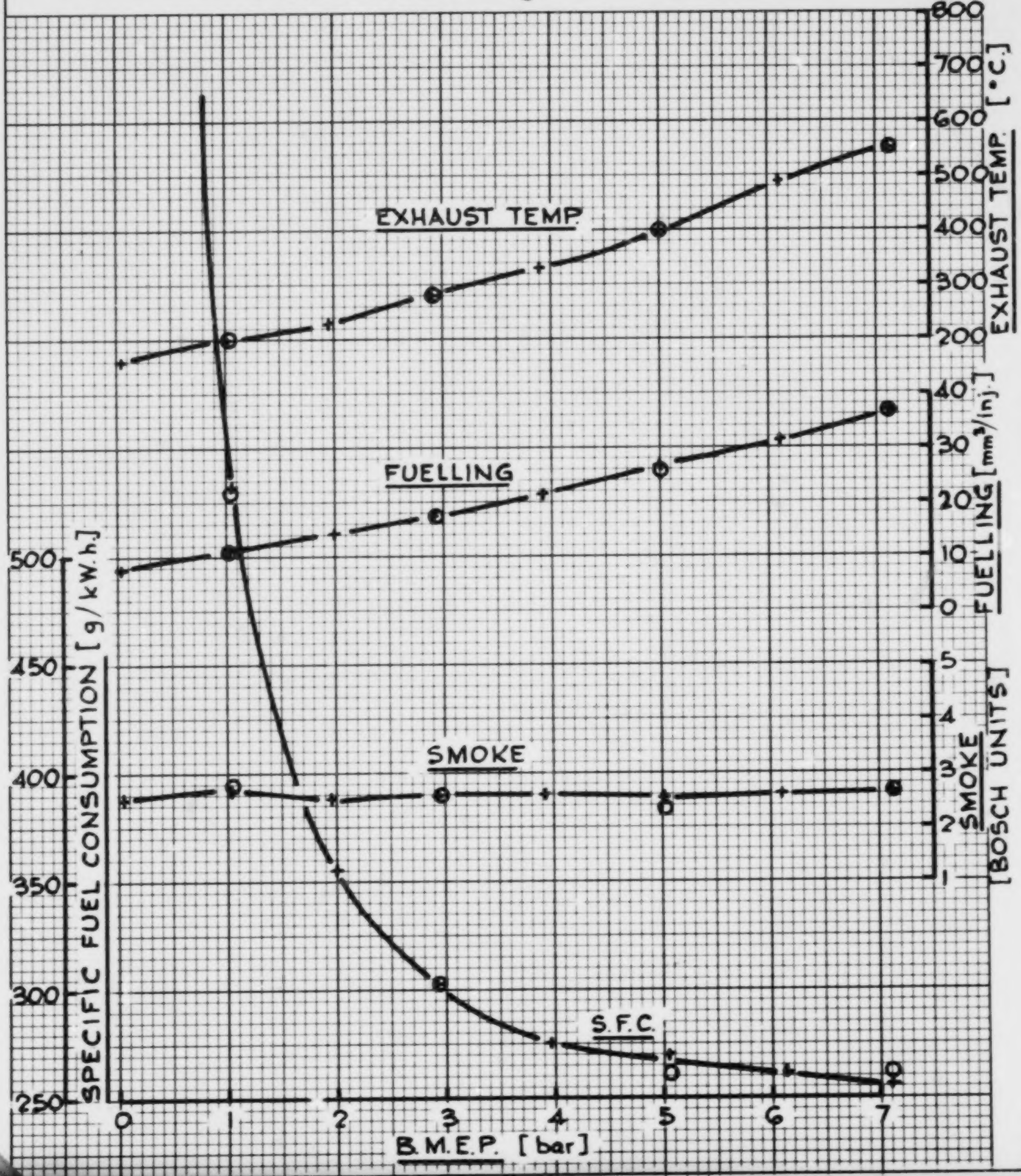
FIG. No. 43
Drg. No. D34936
Date AUG. '77
Engine Curve No. 34

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.
LOAD RANGE PERFORMANCE AT 35 rev/s.

TURBOCHARGED BUILD

+———+ FIRST TEST ⊙- - - -⊙ REPLICATE TEST

BARO: 754·2 mm Hg AIT. 19-24°C



RICARDO CONSULTING ENGINEERS

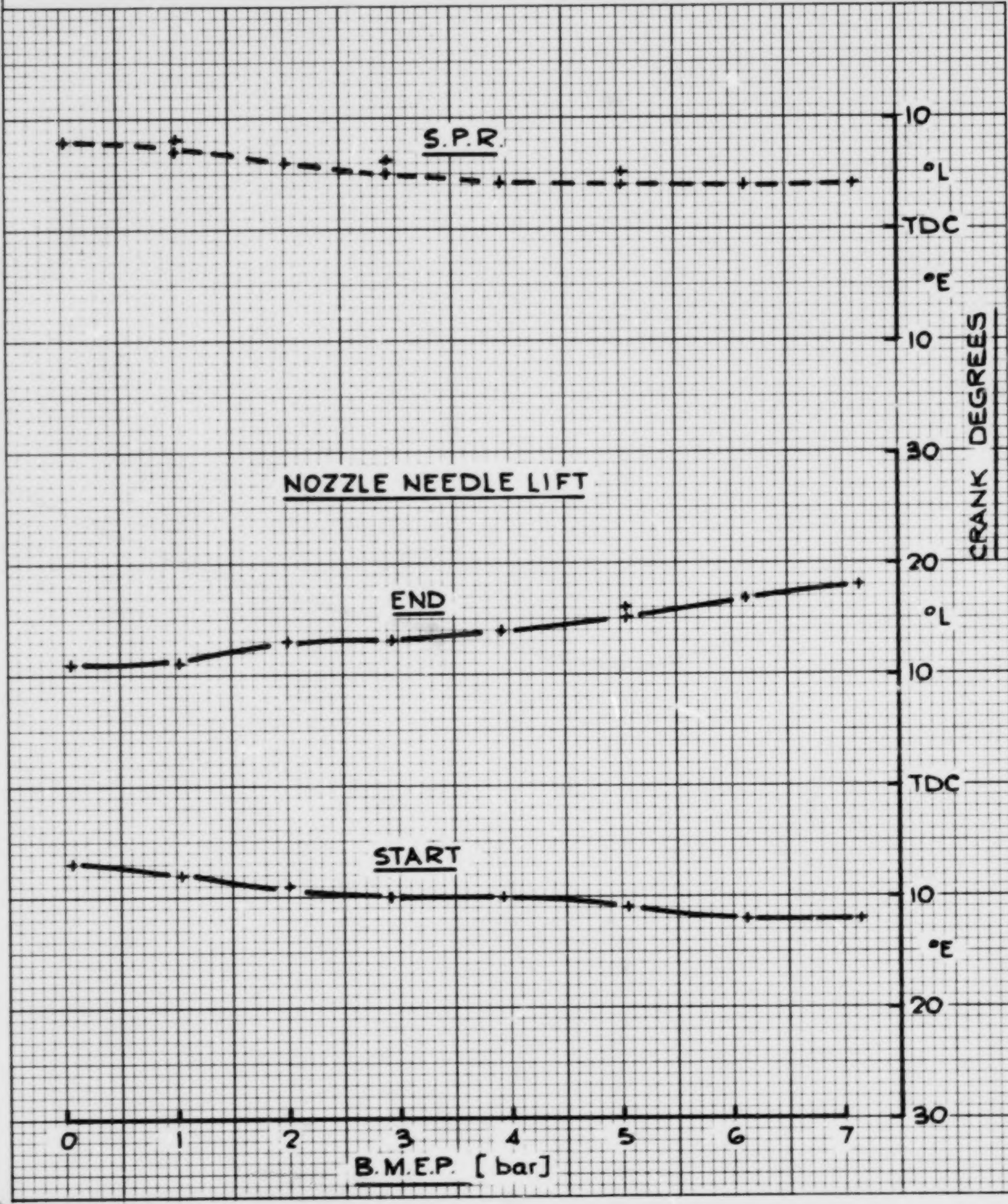
FIG. No. 44
Drg. No. D34937
Date AUG.'77
Engine Curve No. 34a

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91mm x 92.4mm x 5 CYL.

DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 35 rev/s.

TURBOCHARGED BUILD

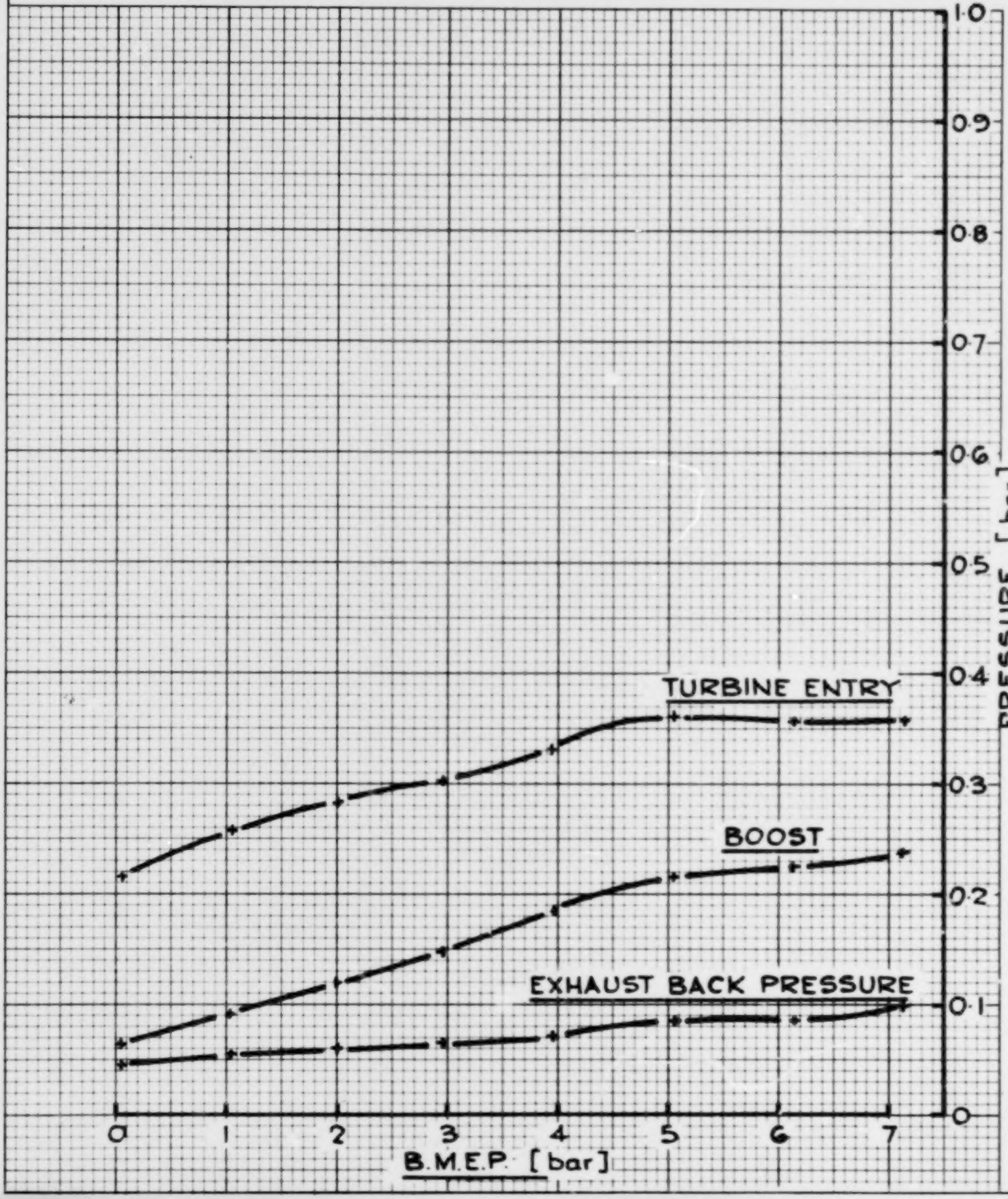


RICARDO CONSULTING ENGINEERS

FIG. No. 45
Drg. No. D34938
Date AUG.'77
Engine Curve No. 36

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
TURBOCHARGER PERFORMANCE AT 35 rev/s.

TURBOCHARGED BUILD



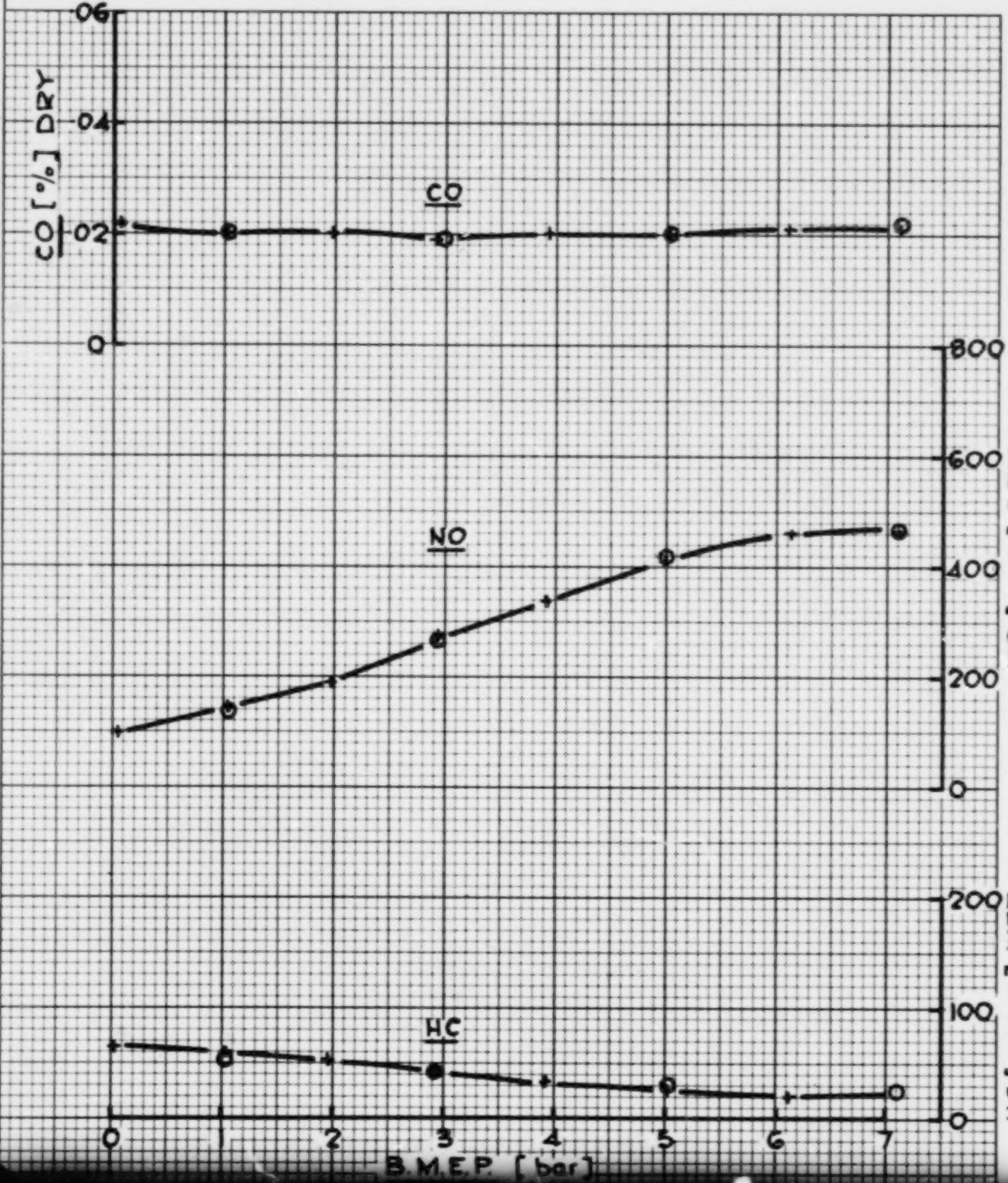
RICARDO CONSULTING ENGINEERS

FIG. No. 46
Drg. No. D34939
Date AUG.'77
Engine Curve No. 35

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5CYL.
HC, CO AND NO EMISSIONS AT 35 rev/s

TURBOCHARGED BUILD

+———+ FIRST TEST ⊙– – – –⊙ REPLICATE TEST



RICARDO CONSULTING ENGINEERS

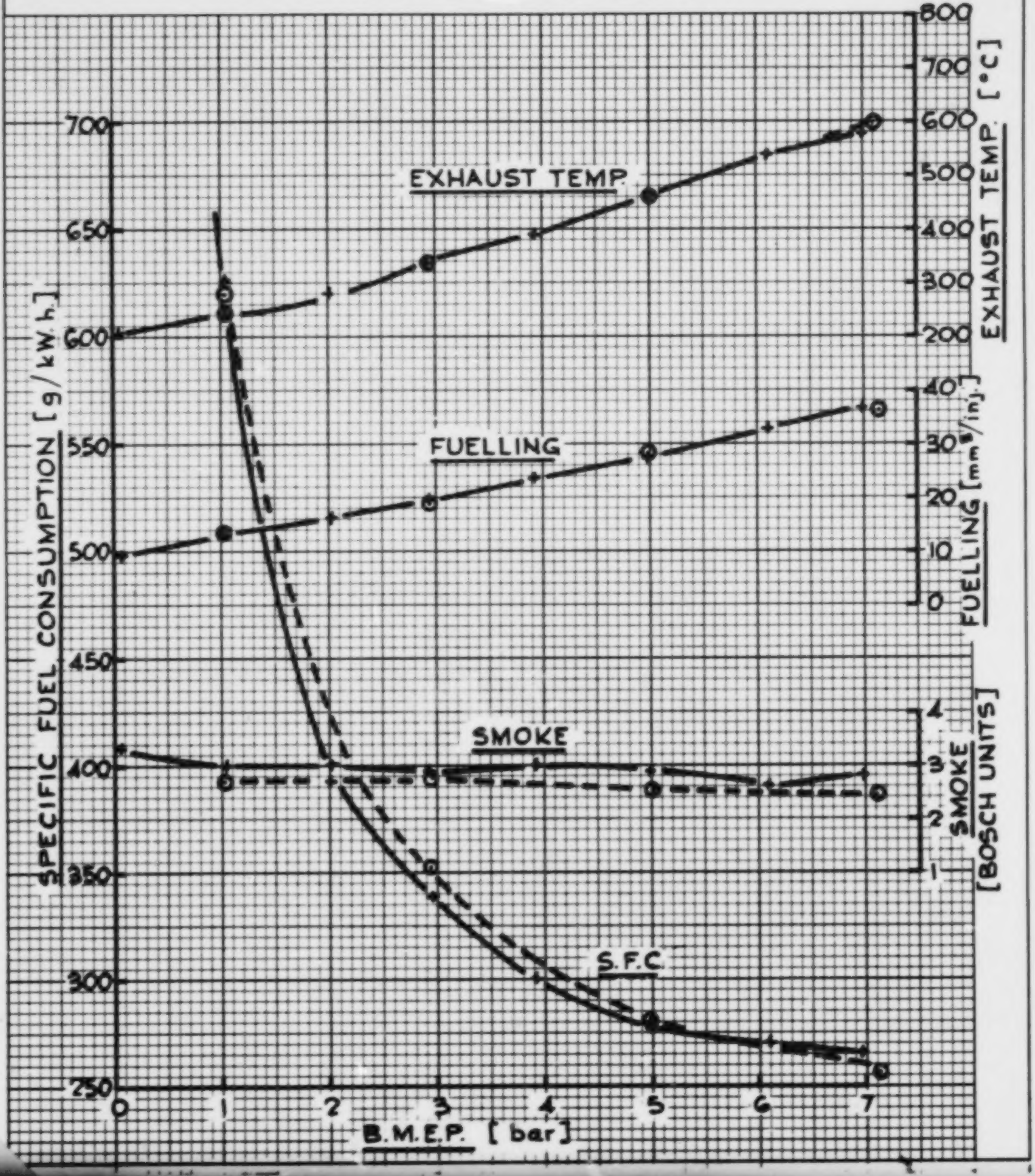
FIG. No. 47
Drg. No. D34940
Date AUG.'77
Engine Curve No. 37

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.
LOAD RANGE PERFORMANCE AT 45 rev/s

TURBOCHARGED BUILD

+———+ FIRST TEST   - - - - ⊙ REPLICATE TEST

BARO: 753·4 mm   AIT 18-22°C



RICARDO CONSULTING ENGINEERS

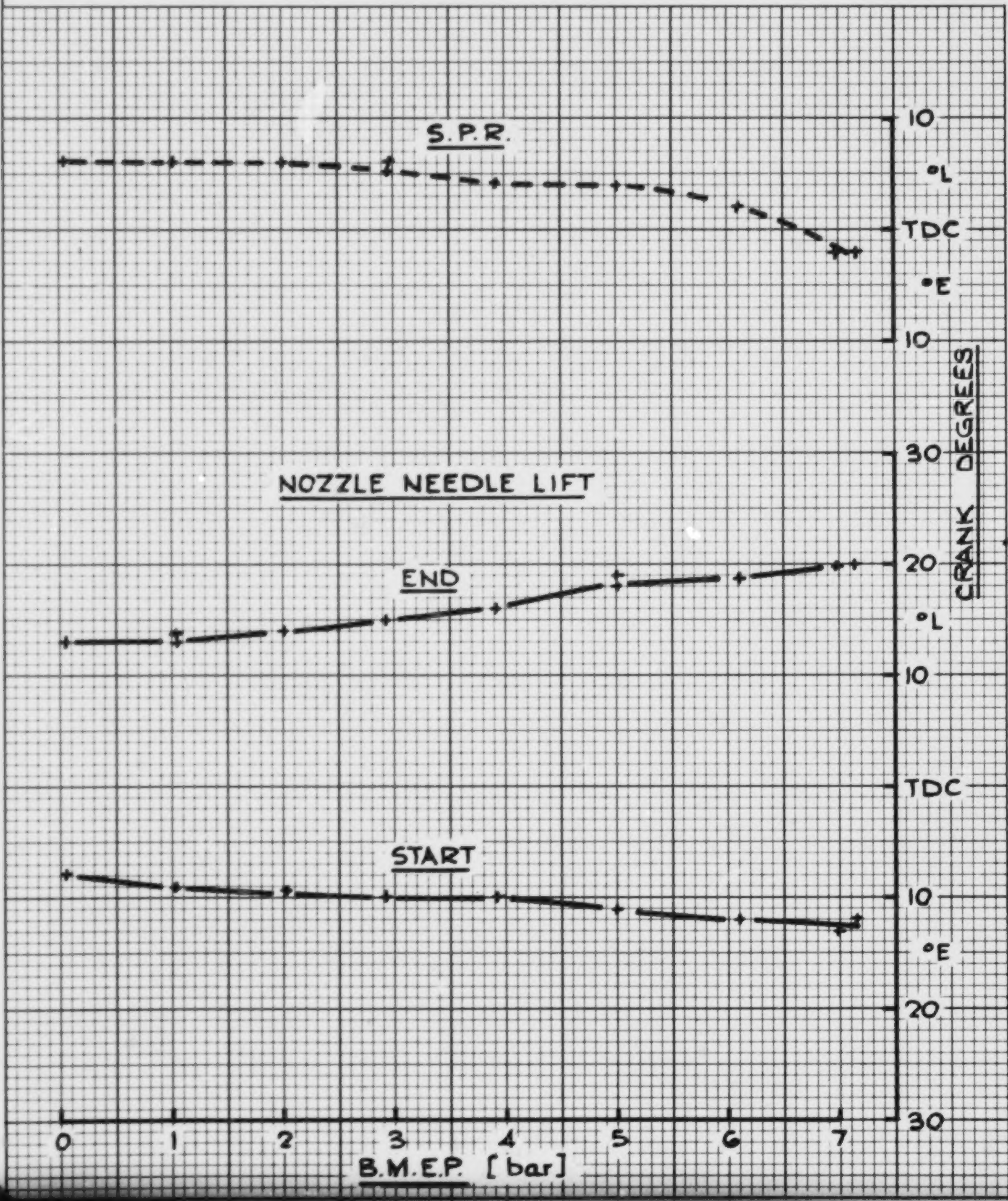
FIG. No. 48
Drg. No. D34941
Date AUG. '77
Engine Curve No. 37a

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92.4 mm x 5 CYL.

DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 45 rev/s.

TURBOCHARGED BUILD

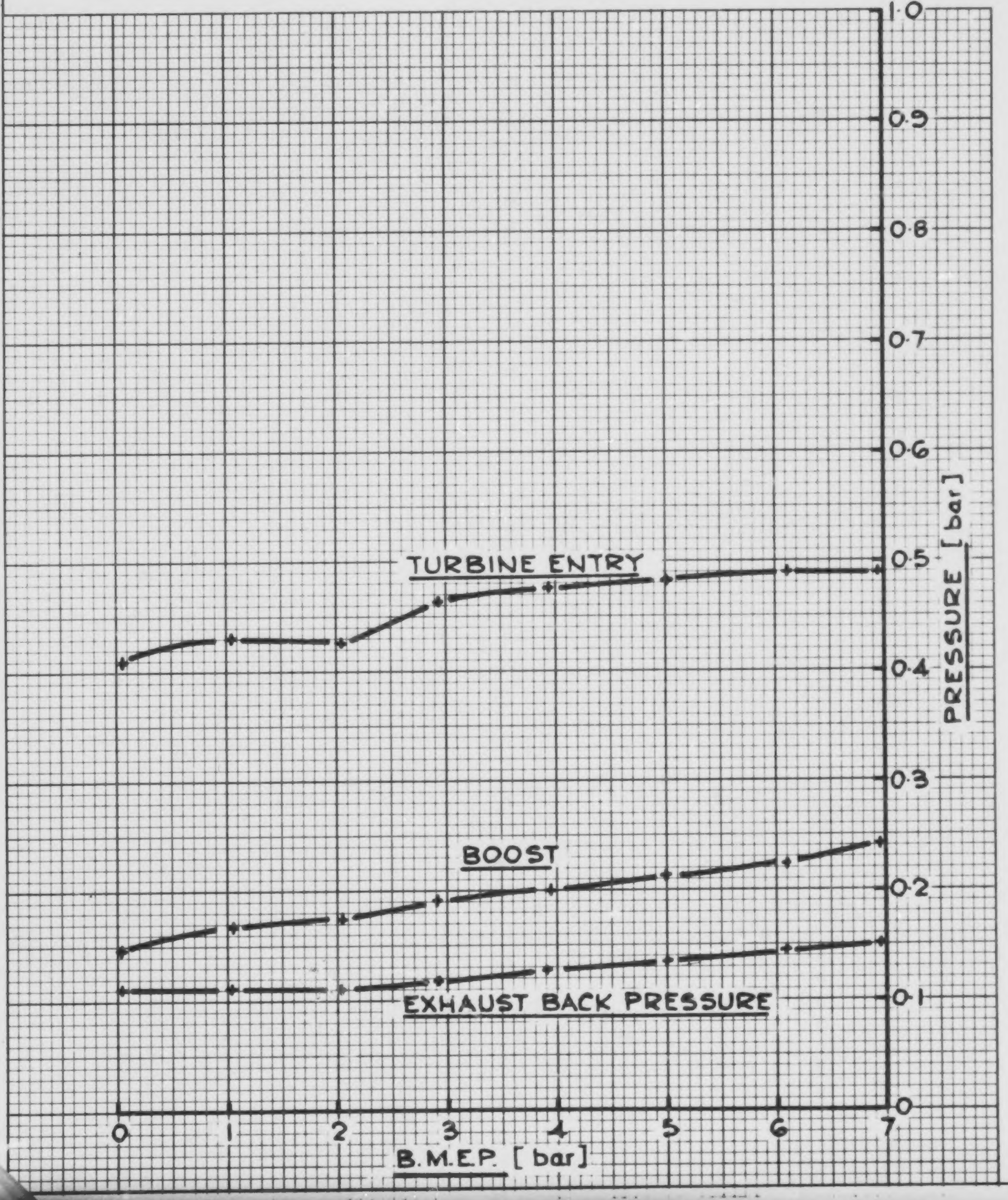


RICARDO CONSULTING ENGINEERS

FIG. No. 49
Drg. No. D34942
Date AUG. '77
Engine Curve No. 39

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92.4mm x 5 CYL.
TURBOCHARGER PERFORMANCE AT 45 rev/s.

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 50
Drg. No. D34943
Date AUG. '77
Engine Curve No. 38

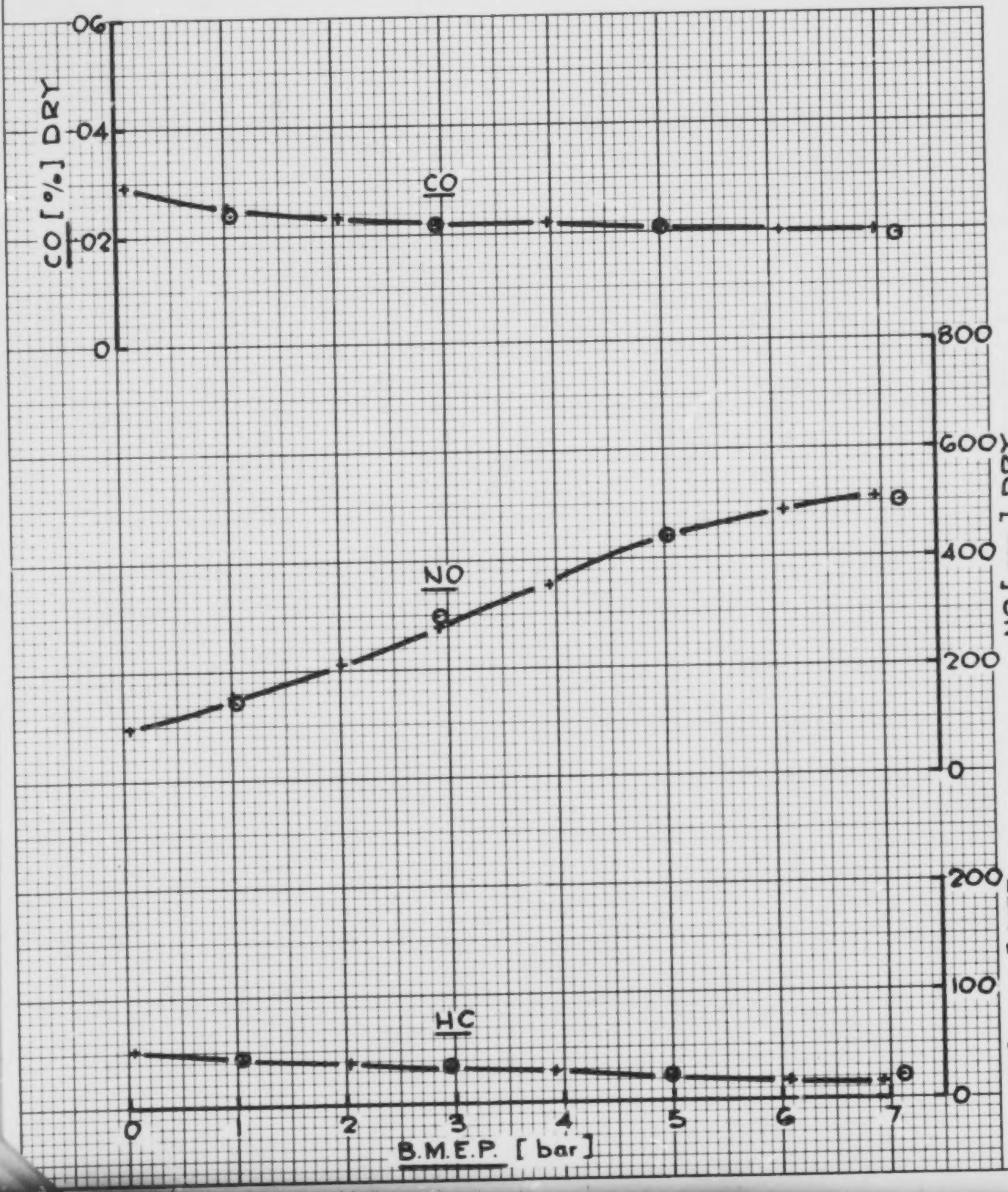
EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92.4 mm x 5 CYL.

HC, CO AND NO EMISSIONS AT 45 rev/s.

TURBOCHARGED BUILD

+———+ FIRST TEST ⊙– – – –⊙ REPLICATE TEST



RICARDO CONSULTING ENGINEERS

FIG. No. 51
Drg. No. D34944
Date AUG.'77
Engine Curve No. 40

EPA MODULATED EGR STUDY

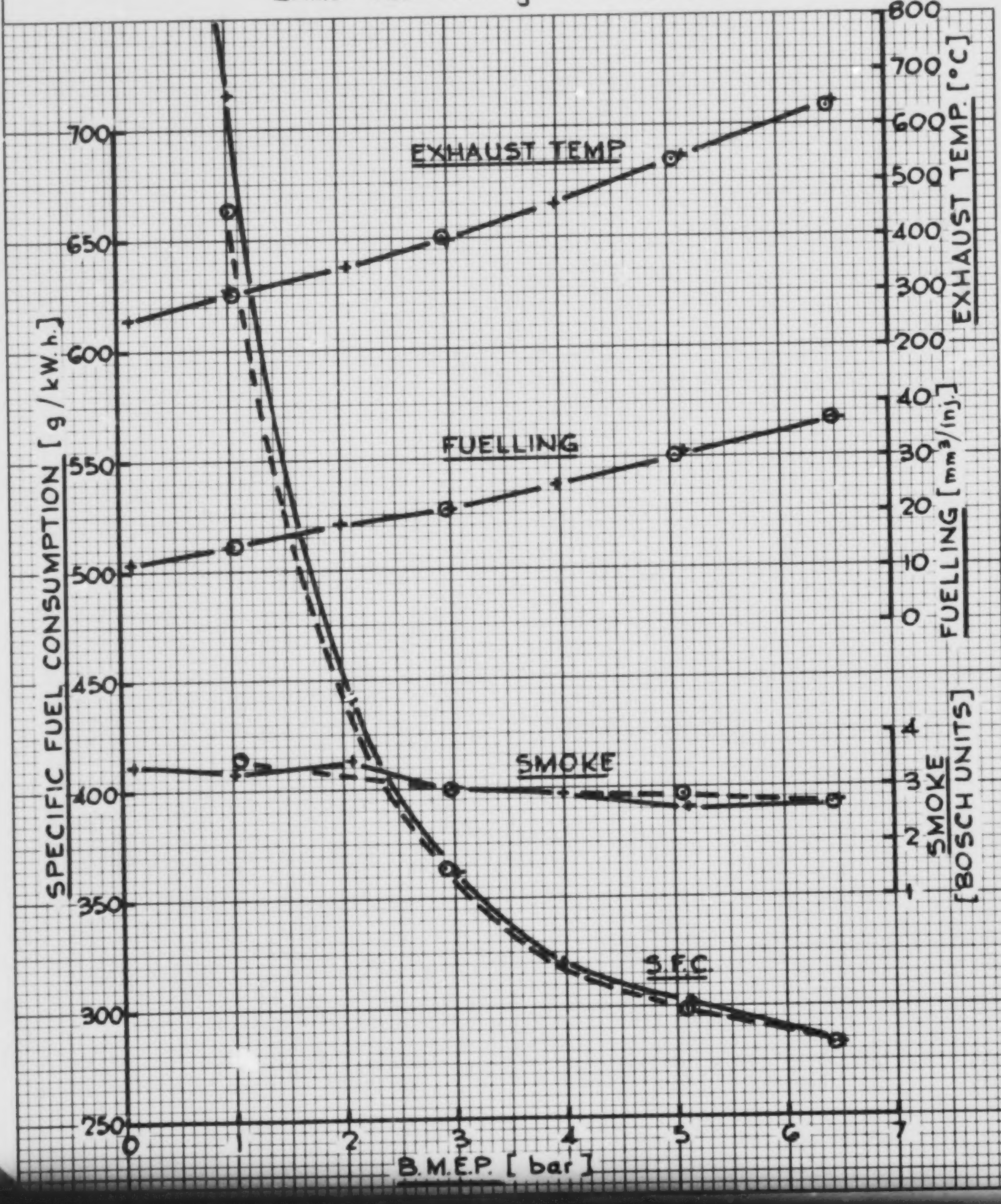
MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.

LOAD RANGE PERFORMANCE AT 55 rev/s

TURBOCHARGED BUILD

+———+ FIRST TEST   ⊙– – – –⊙ REPLICATE TEST

BARO: 752·6 mm Hg   AIT 18-19°C



RICARDO CONSULTING ENGINEERS

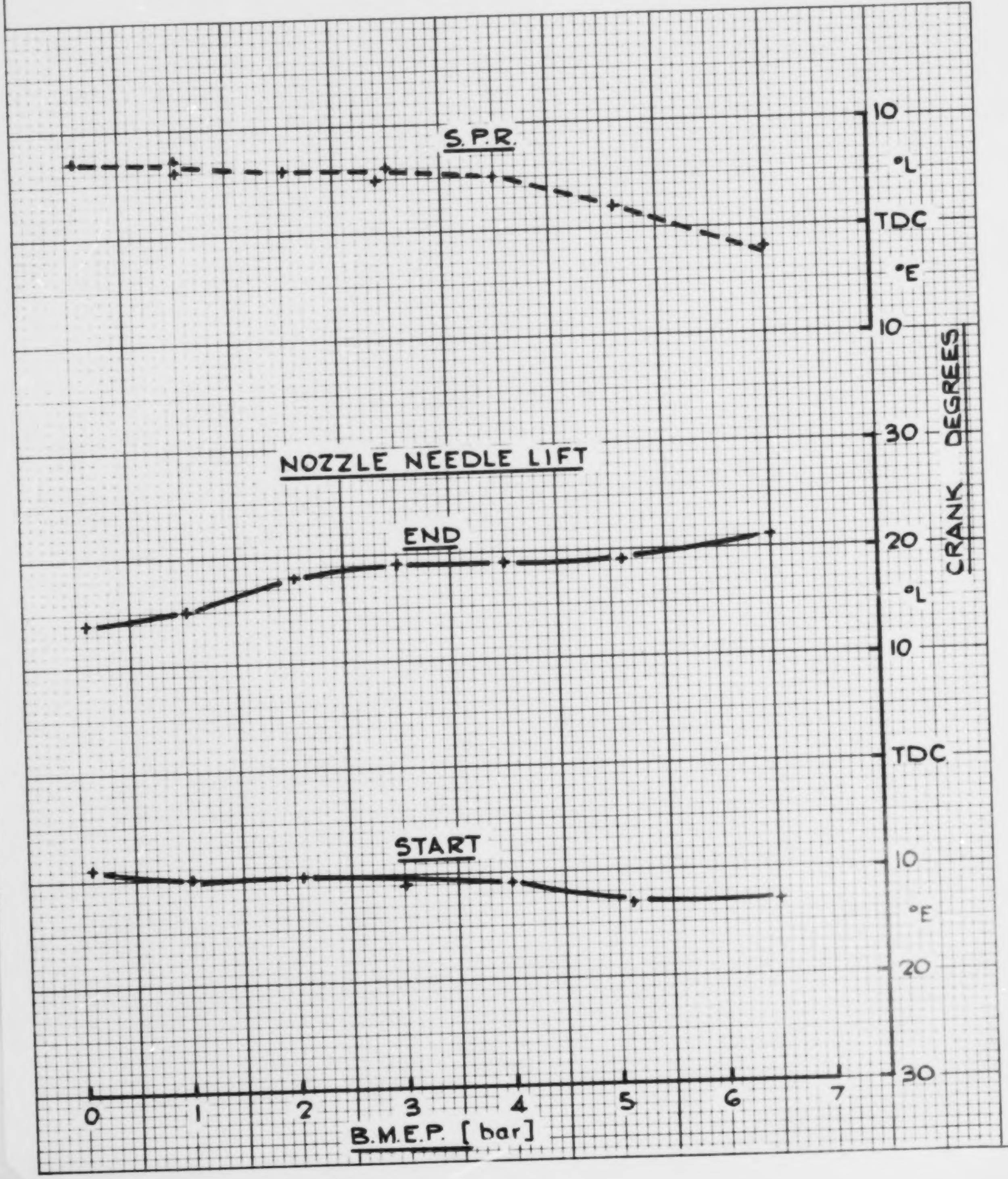
FIG. No. 52
Drg. No. D34945
Date AUG. '77
Engine Curve No. 40a

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 55 rev/s.

TURBOCHARGED BUILD

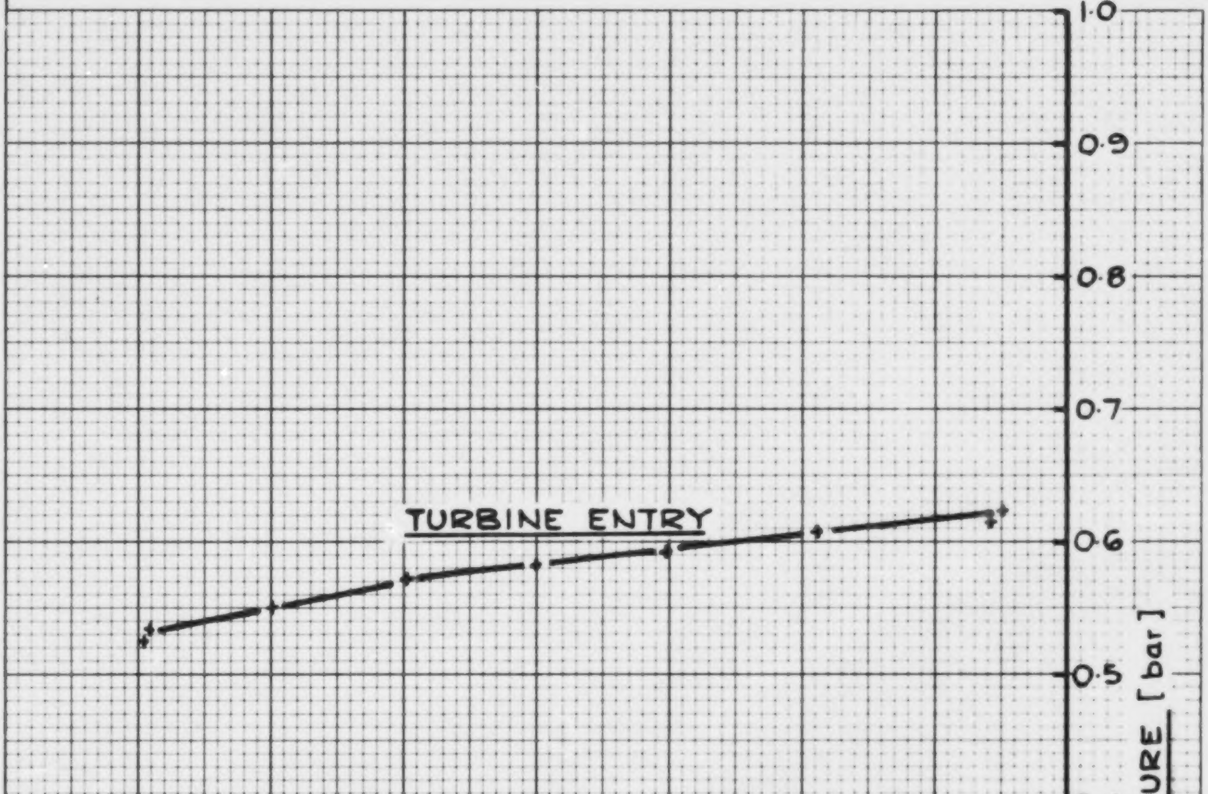


RICARDO CONSULTING ENGINEERS

FIG. No. 53
Drg. No. D34946
Date AUG. '77
Engine Curve No. 42

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5 CYL.
TURBOCHARGER PERFORMANCE AT 55 rev/s.

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

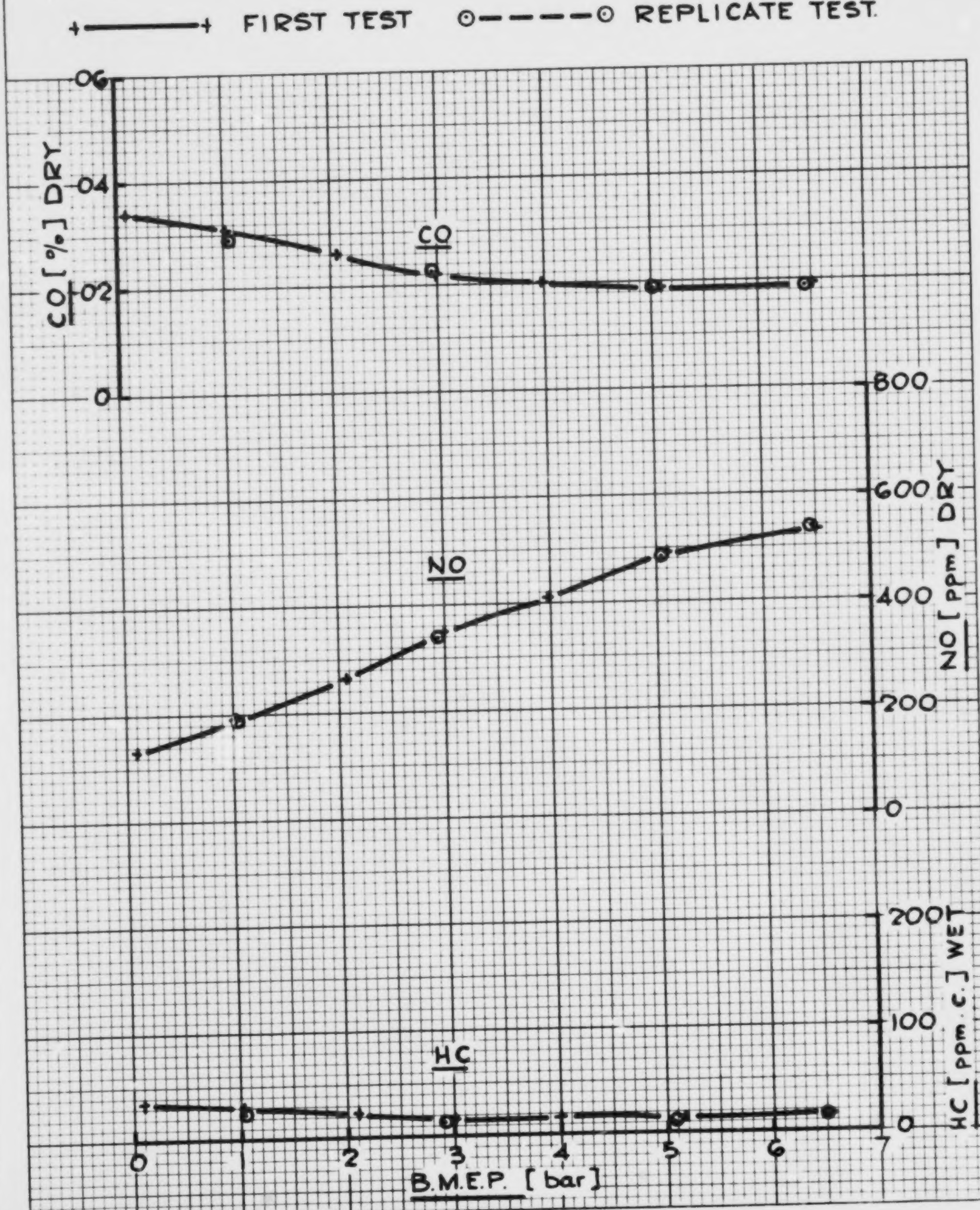
FIG. No. 54
Drg. No. D34947
Date AUG. '77
Engine Curve No. 41

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE. 91 mm × 92·4 mm × 5 CYL.

HC, CO AND NO EMISSIONS AT 55 rev/s.

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

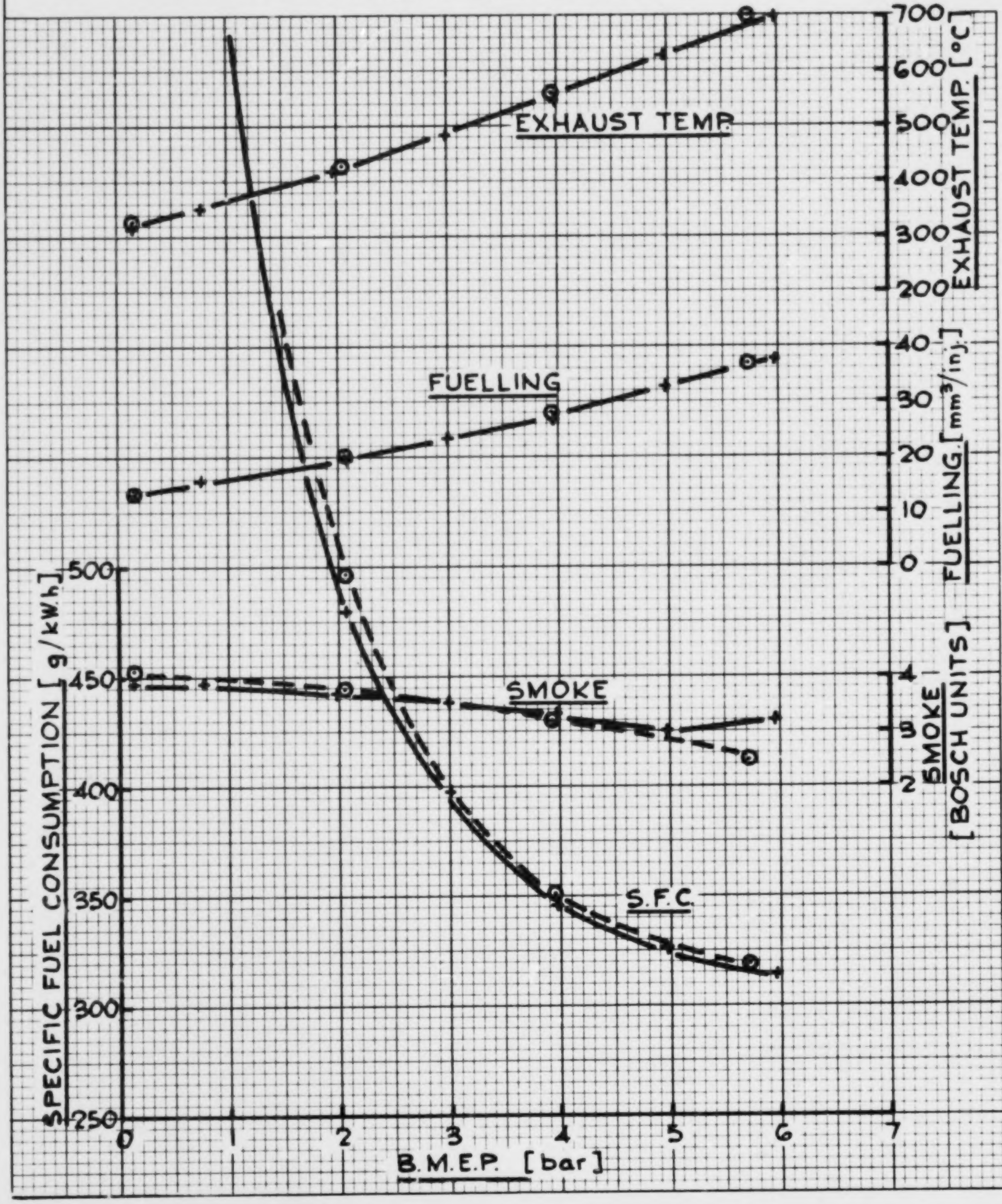
FIG. No. 55
Drg. No. D34948
Date AUG. '77
Engine Curve No. 43

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.
LOAD RANGE PERFORMANCE AT 65 rev/s.

TURBOCHARGED BUILD

+——+ FIRST TEST ⊙- - - -⊙ REPLICATE TEST

BARO: 753·8 AIT 19-23°C



RICARDO CONSULTING ENGINEERS

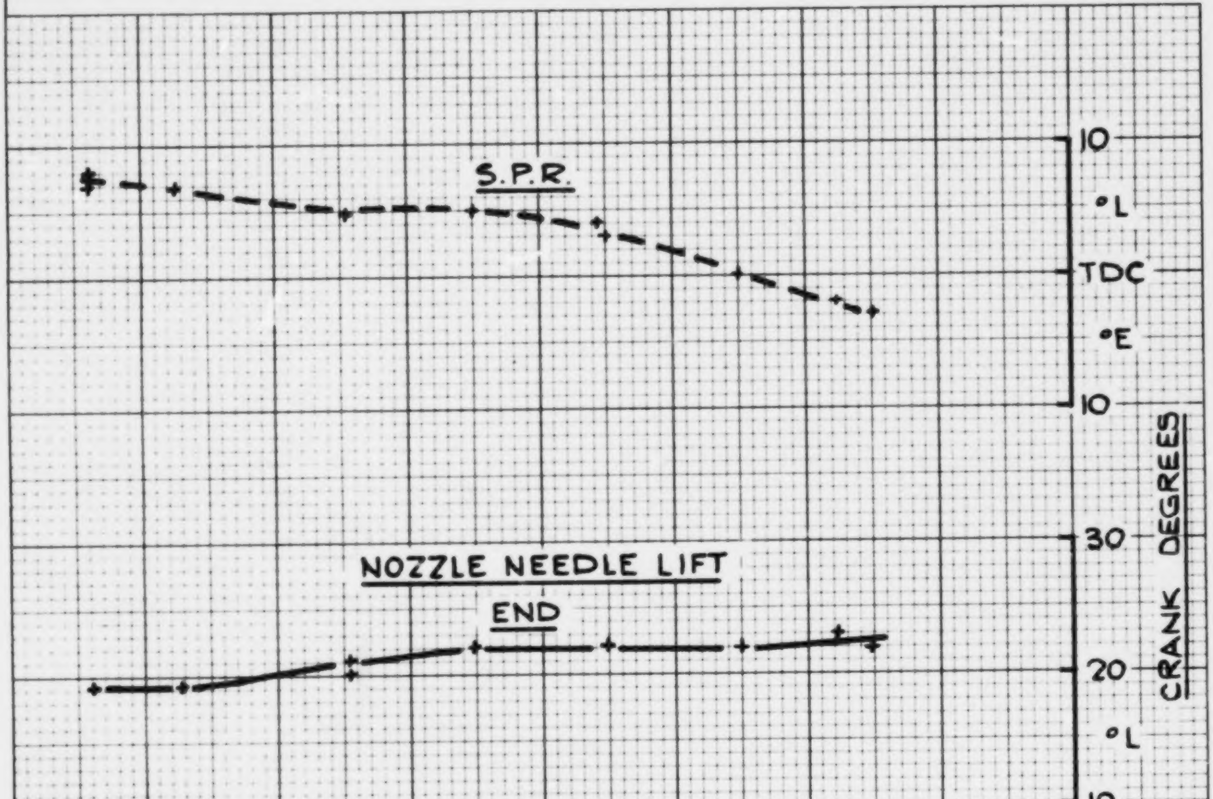
FIG. No. 56
Drg. No. D34949
Date AUG.'77
Engine Curve No. 43a

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm × 92·4 mm × 5 CYL.

DYNAMIC NOZZLE NEEDLE LIFT AND START OF PRESSURE RISE AT 65 rev/s

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 57

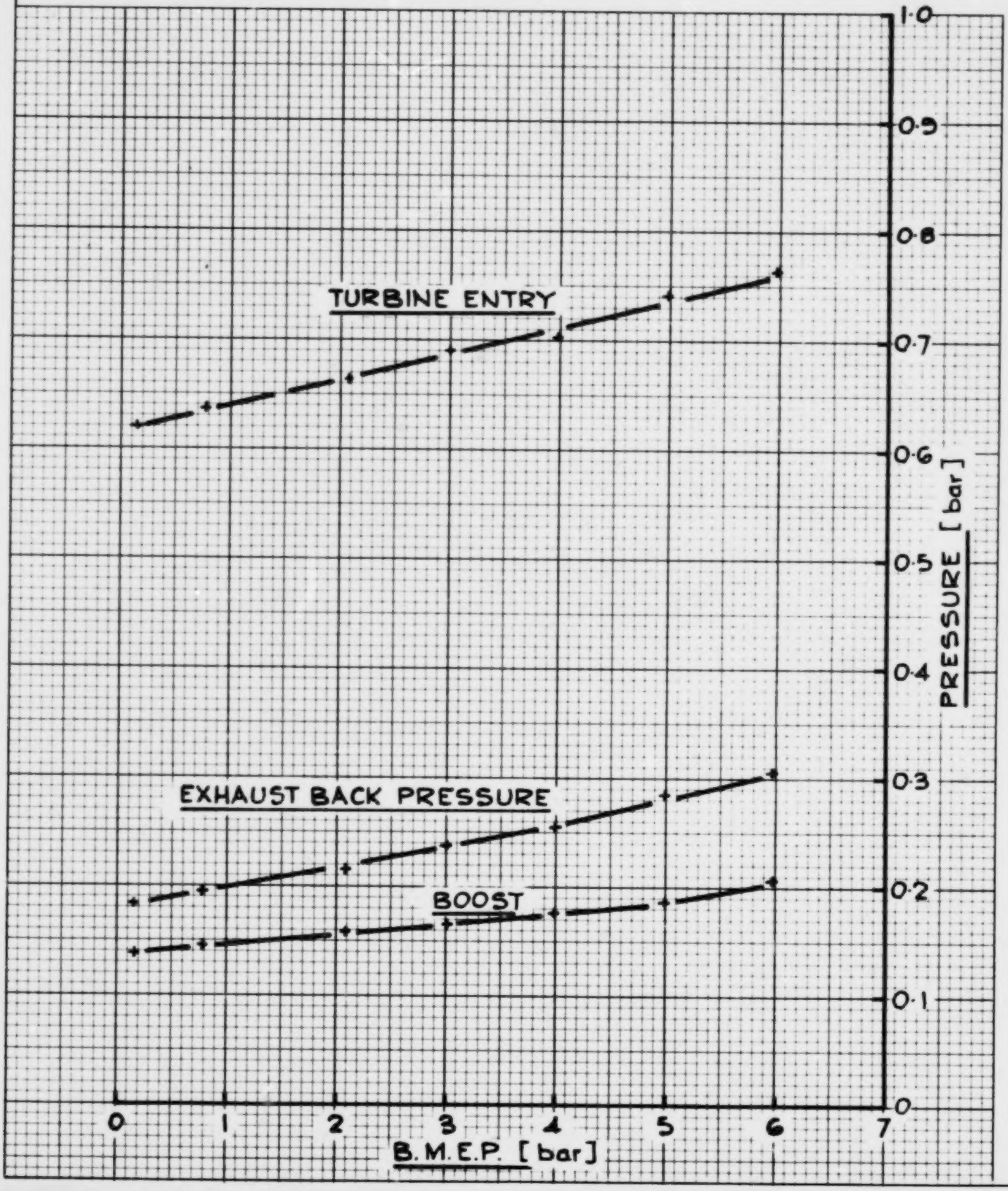
Drg. No. 034950

Date AUG. '77

Engine Curve 45

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
TURBOCHARGER PERFORMANCE AT 65 rev/s

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

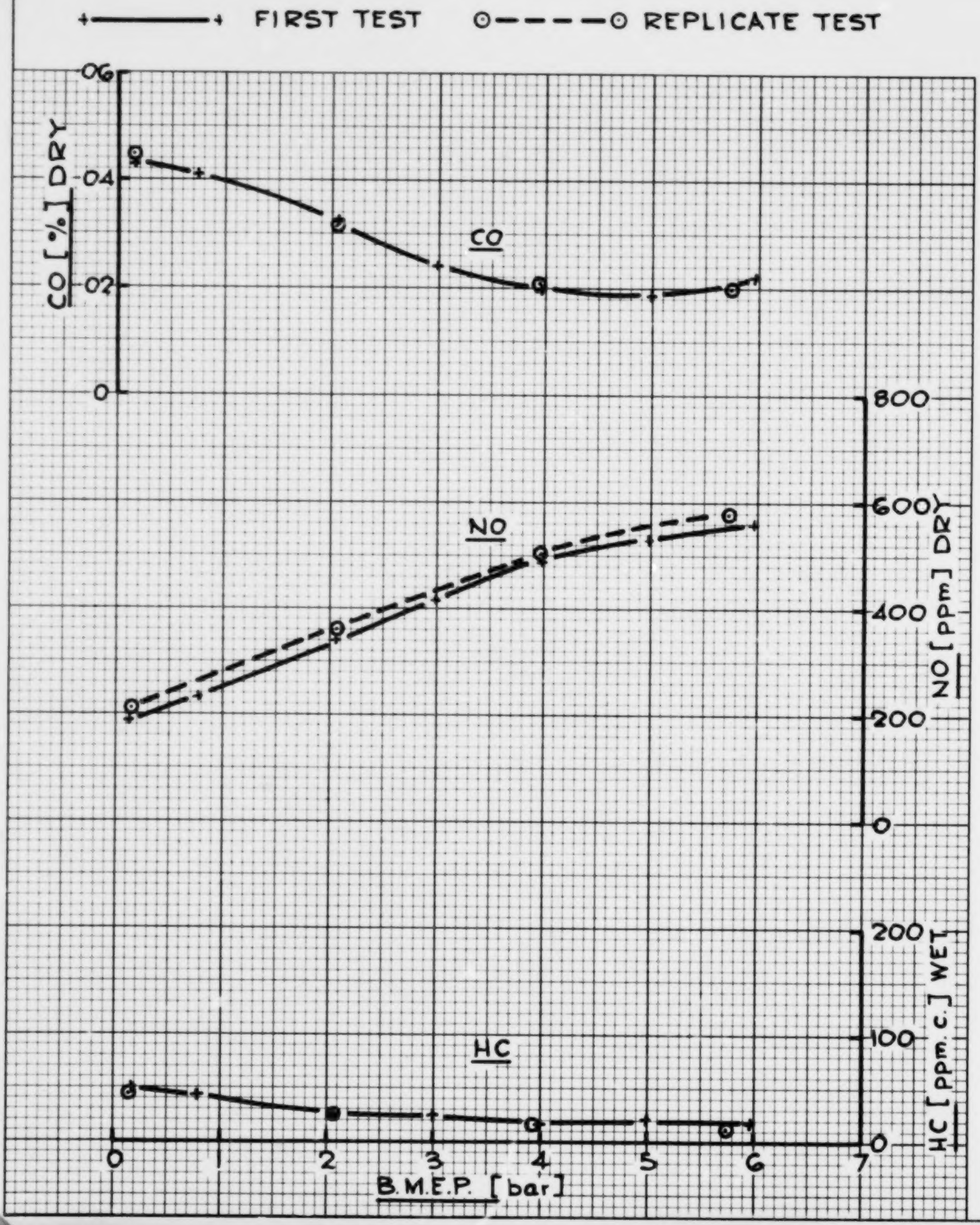
FIG. No. 58
Drg. No. D34951
Date AUG.'77
Engine Curve 44

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.

HC, CO AND NO EMISSIONS AT 65 rev/s.

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

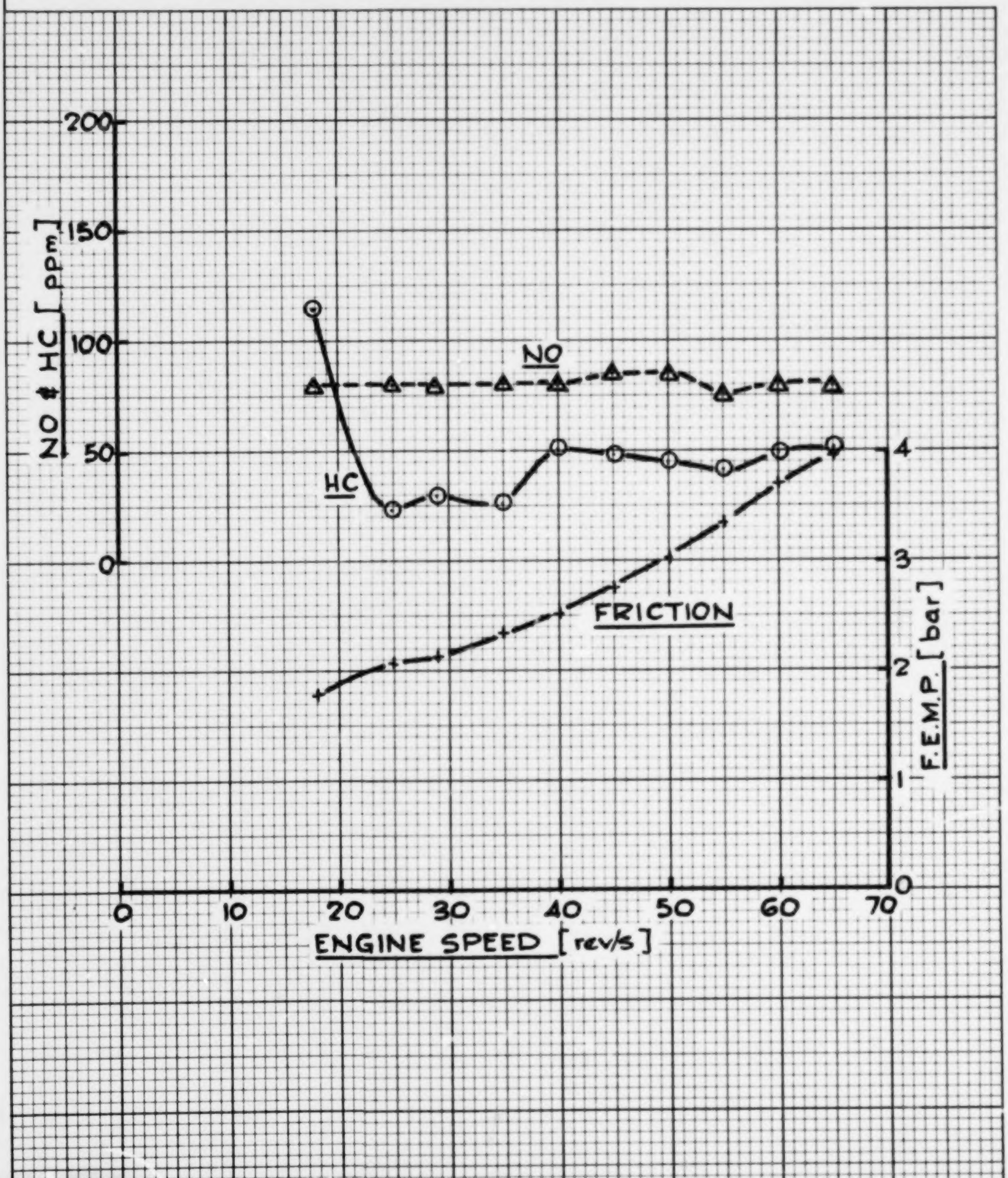
FIG. No. 59
Drg. No. D34952
Date AUG.'77
Engine Curve No. 54

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm × 92·4mm × 5CYL.

MOTORING FRICTION AND EMISSIONS UNDER OVERRUN CONDITIONS.

TURBOCHARGED BUILD

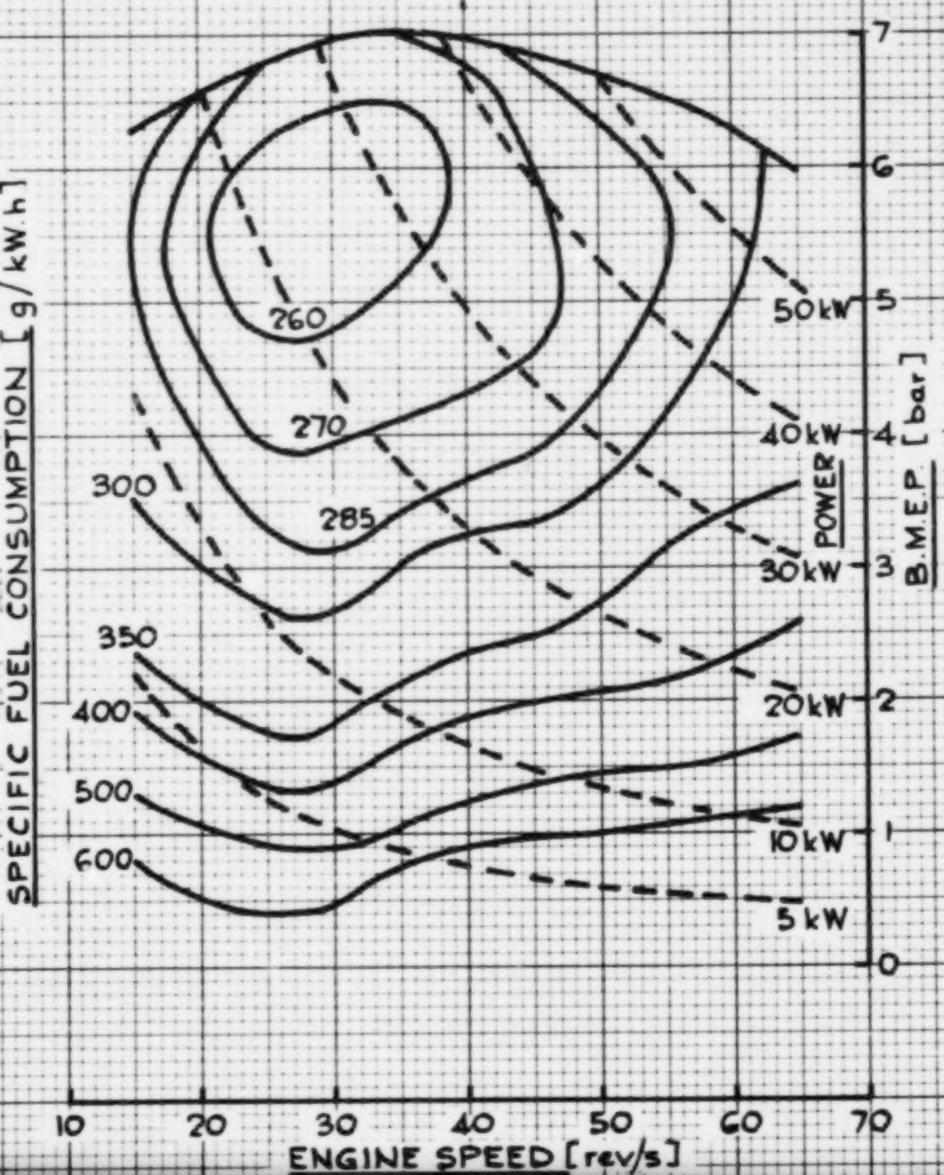


RICARDO CONSULTING ENGINEERS

FIG. No. 60
Drg. No. D34953
Date AUG '77
Engine Curve 20

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.
COMPOSITE SPECIFIC FUEL CONSUMPTION MAP

STANDARD AS RECEIVED BUILD



RICARDO CONSULTING ENGINEERS

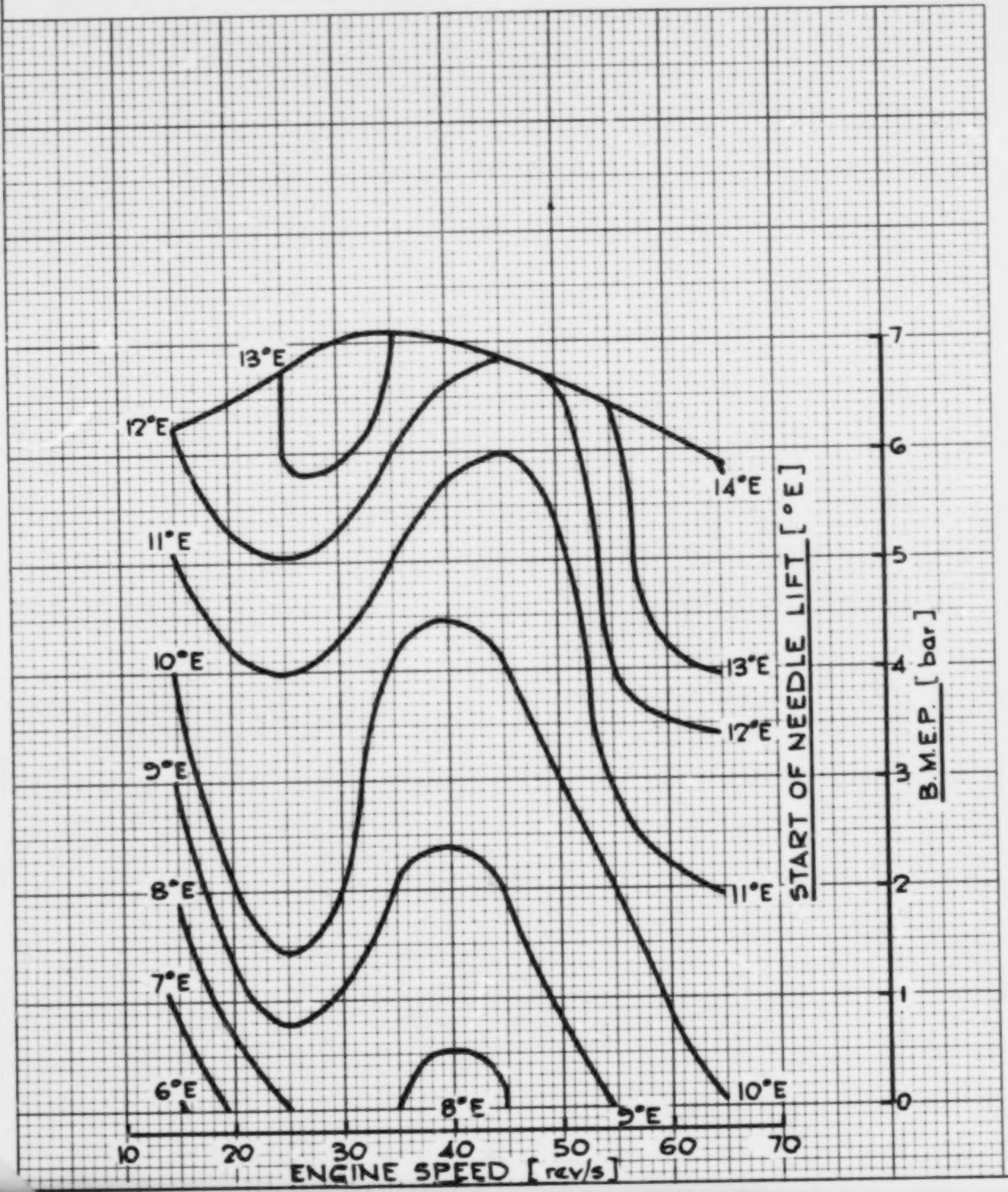
FIG. No. 61
Drg. No. D34954
Date AUG.'77
Engine Curve 21

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92.4mm x 5 CYL.

COMPOSITE MAP OF START OF DYNAMIC NOZZLE NEEDLE LIFT

STANDARD AS RECEIVED BUILD

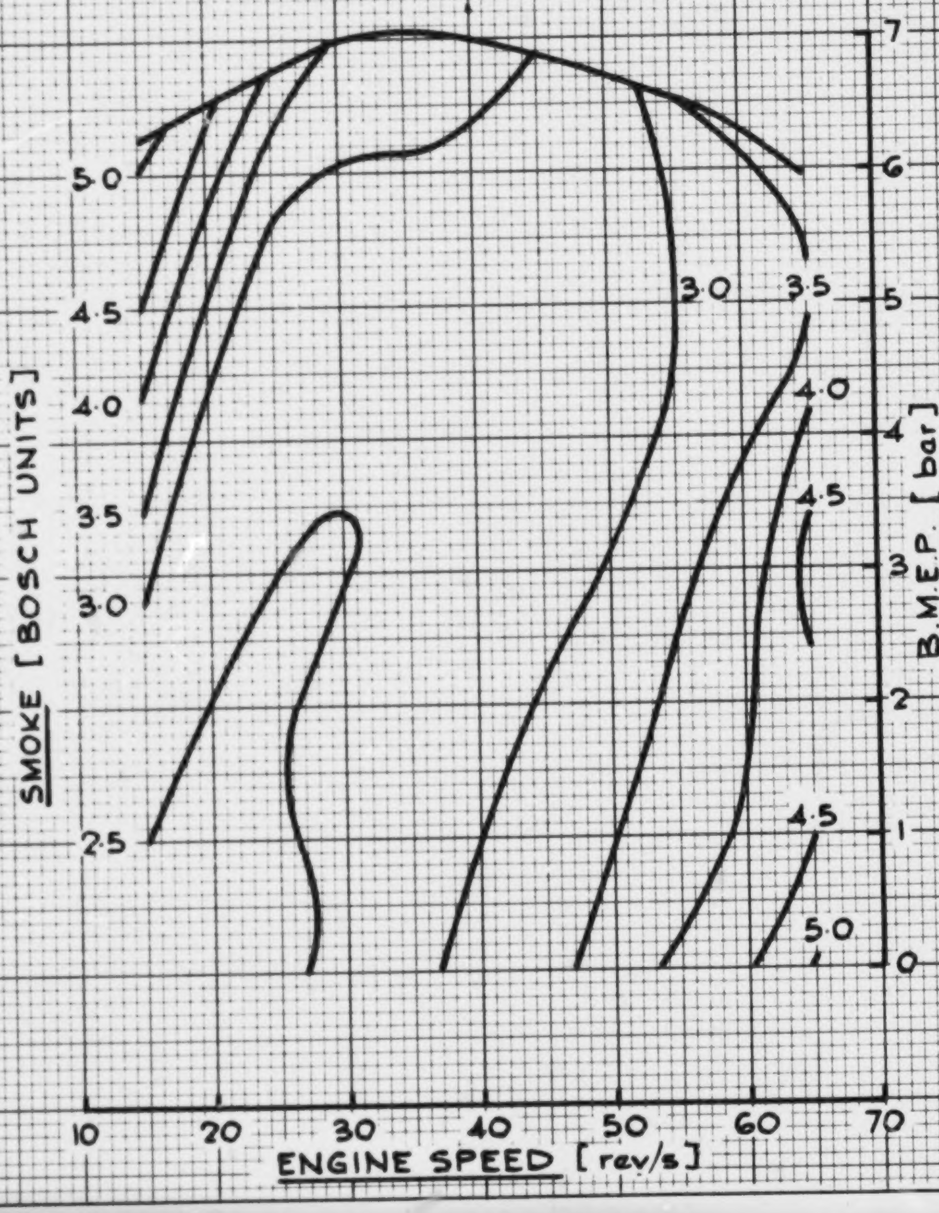


RICARDO CONSULTING ENGINEERS

FIG. No. 62
Drg. No. D34955
Date AUG. '77
Engine Curve No. 22

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
COMPOSITE MAP OF BOSCH SMOKE

STANDARD AS RECEIVED BUILD

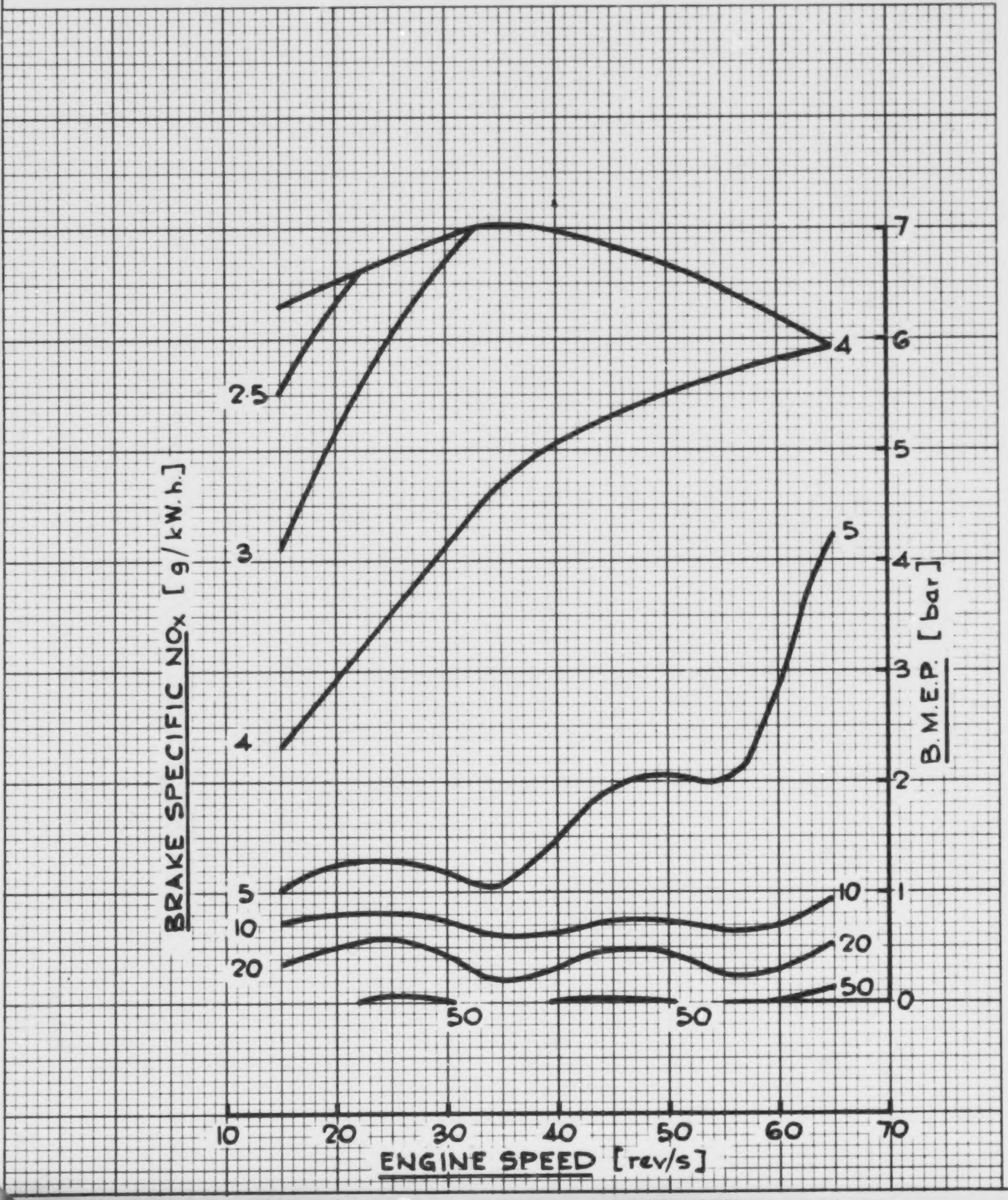


RICARDO CONSULTING ENGINEERS

FIG. No. 63
Drg. No. D34956
Date AUG '77
Engine Curve No. 23

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm × 92·4 mm × 5 CYL.
COMPOSITE MAP OF BRAKE SPECIFIC NO_x EMISSION

STANDARD AS RECEIVED BUILD



RICARDO CONSULTING ENGINEERS

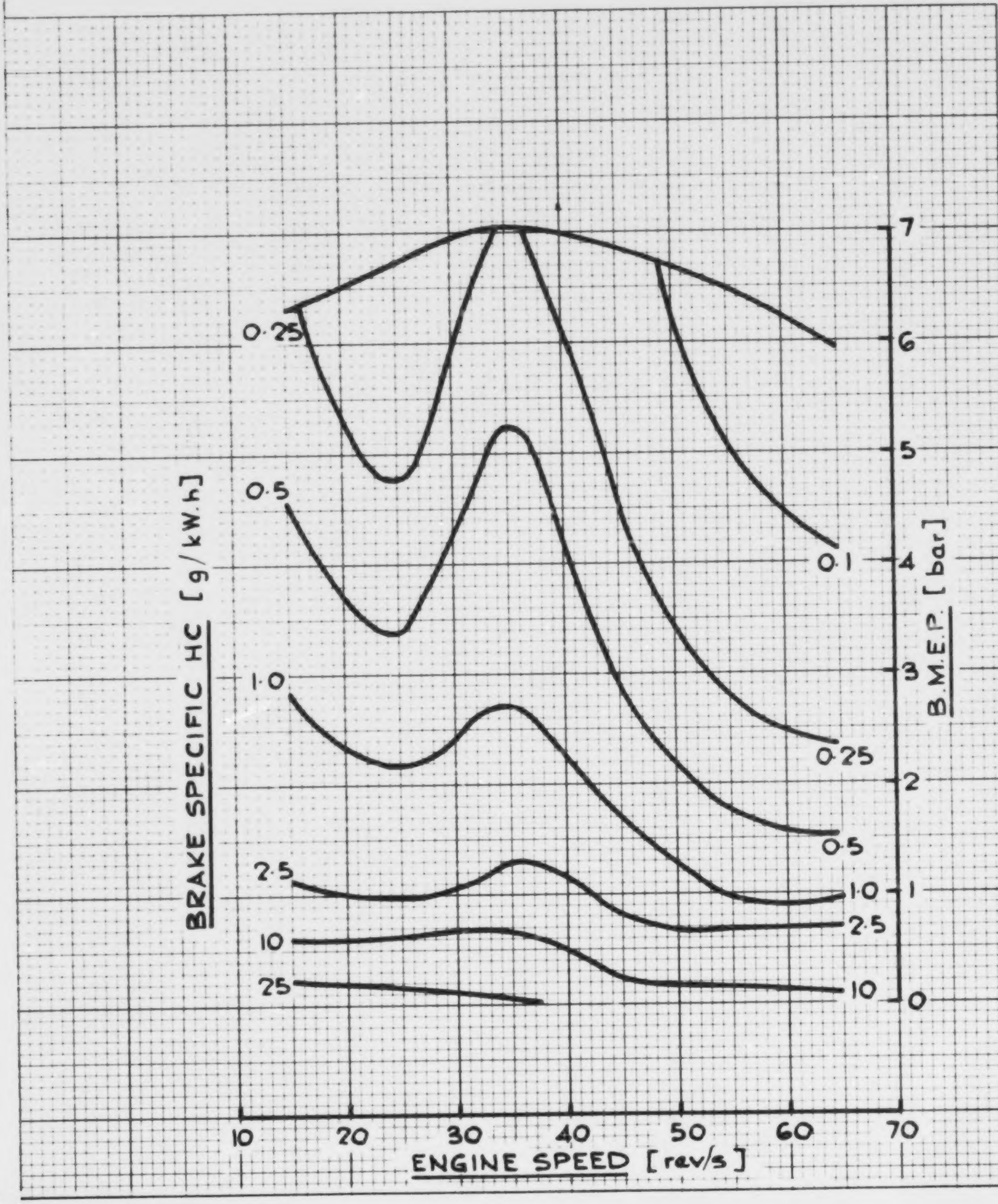
FIG. No. 64
Drg. No. D34957
Date AUG. '77
Engine Curve No. 24

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5 CYL.

COMPOSITE MAP OF BRAKE SPECIFIC HC EMISSION

STANDARD AS RECEIVED BUILD

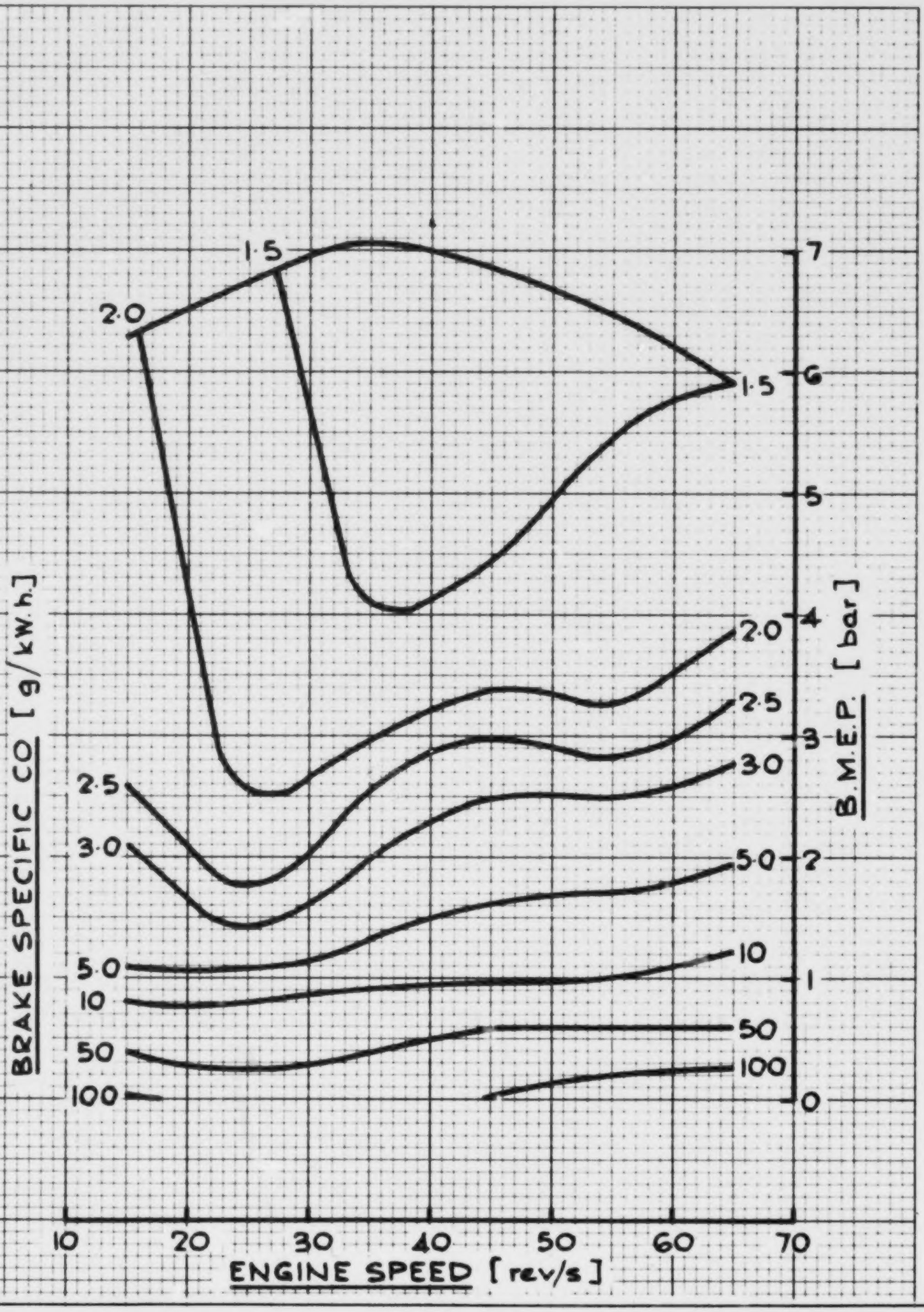


RICARDO CONSULTING ENGINEERS

FIG. No. 65
Drg. No. D34958
Date AUG. '77
Engine Curve 25

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
COMPOSITE MAP OF BRAKE SPECIFIC CO EMISSION

STANDARD AS RECEIVED BUILD

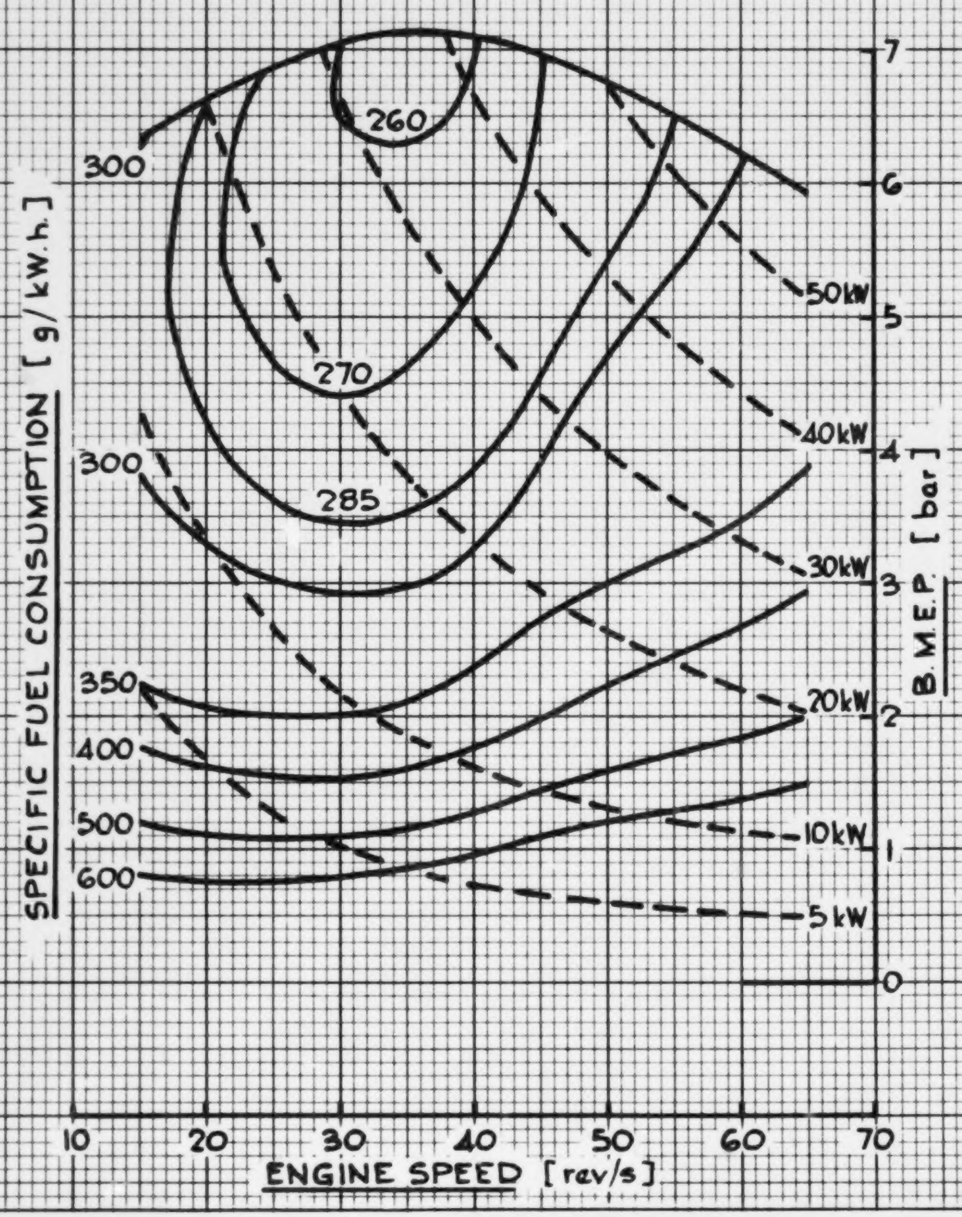


RICARDO CONSULTING ENGINEERS

FIG. No. 66
Drg. No. D34959
Date AUG. '77
Engine Curve 46

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
COMPOSITE SPECIFIC FUEL CONSUMPTION MAP

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

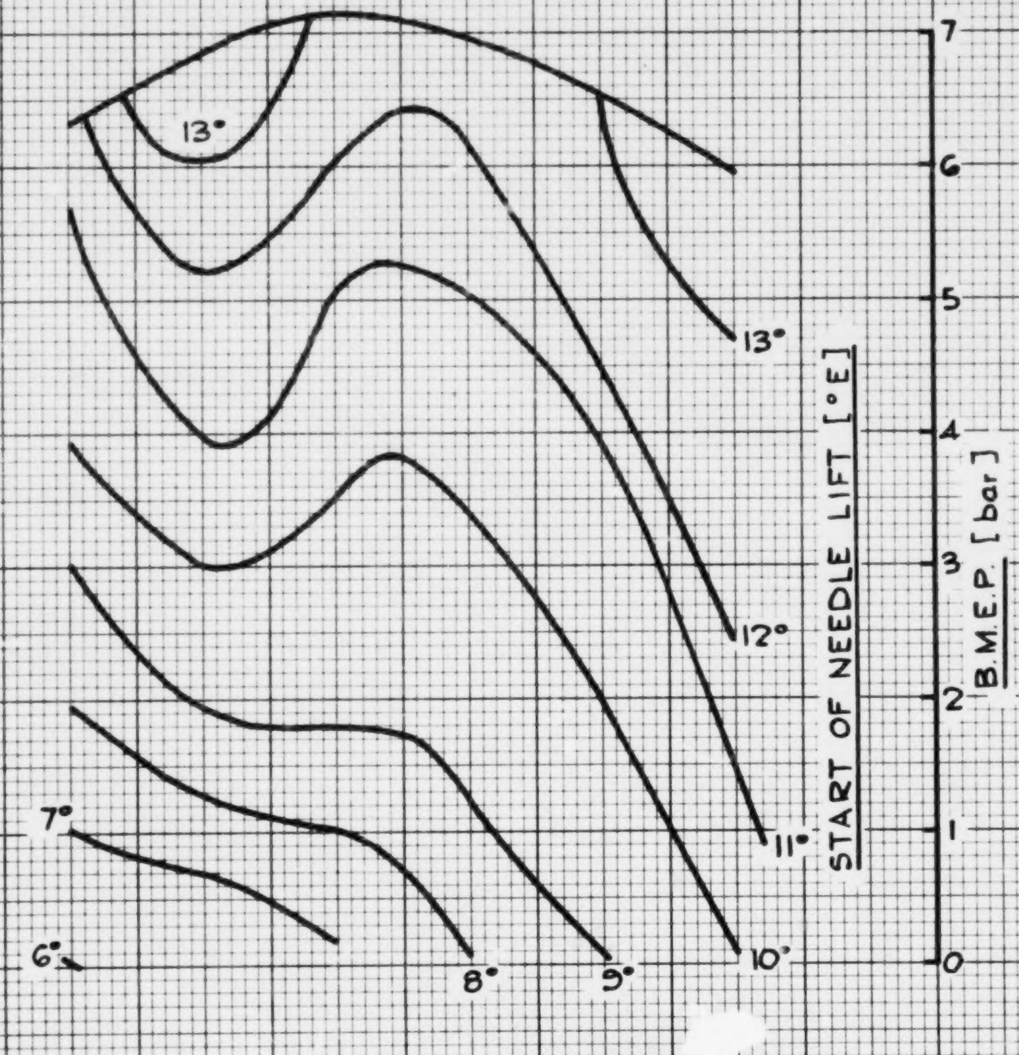
FIG. No. 67
Drg. No. D34960
Date AUG. '77
Engine Curve 47

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91mm x 92.4mm x 5 CYL.

COMPOSITE MAP OF DYNAMIC NOZZLE NEEDLE LIFT

TURBOCHARGED BUILD

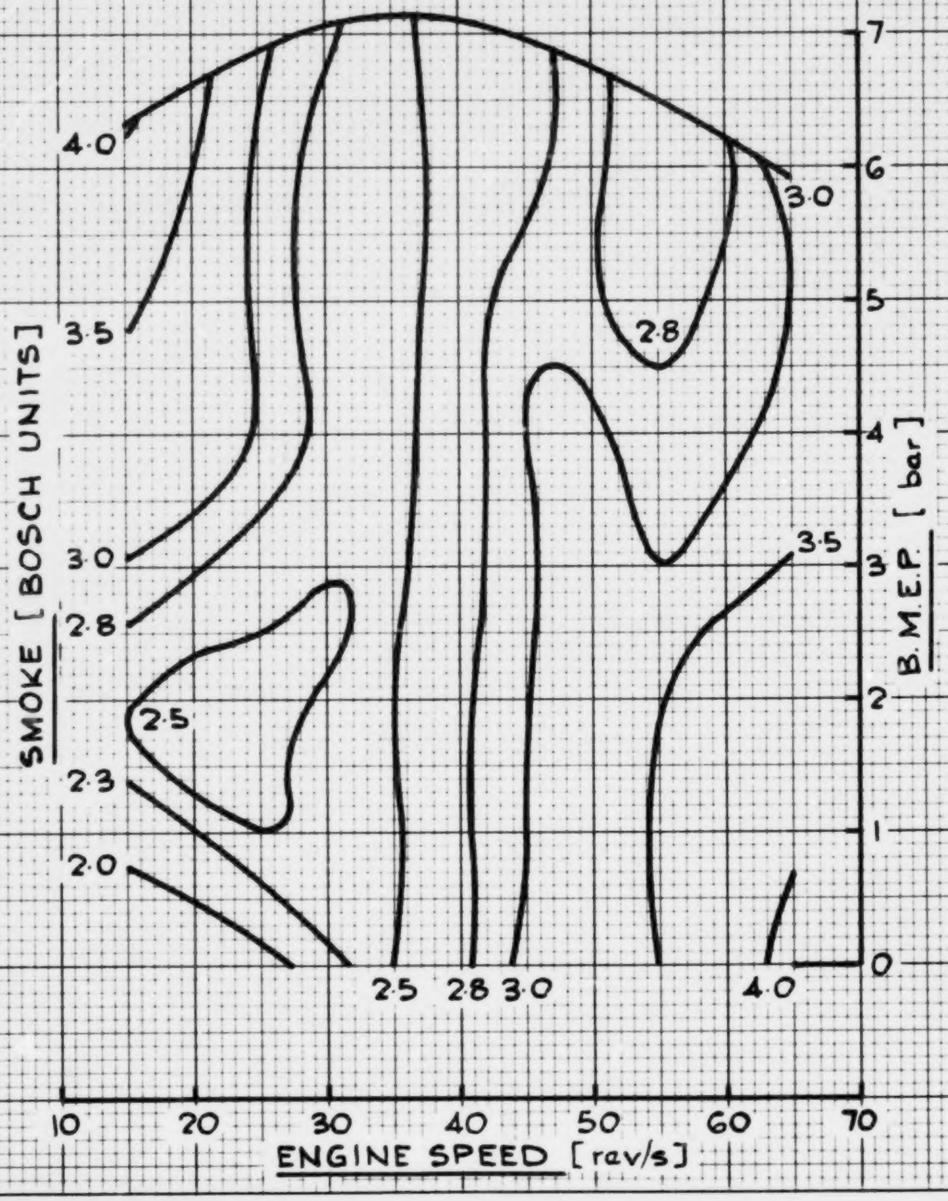


RICARDO CONSULTING ENGINEERS

FIG. No. 68
Drg. No. D34961
Date AUG.'77
Engine Curve 48

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
COMPOSITE MAP OF BOSCH SMOKE

TURBOCHARGED BUILD

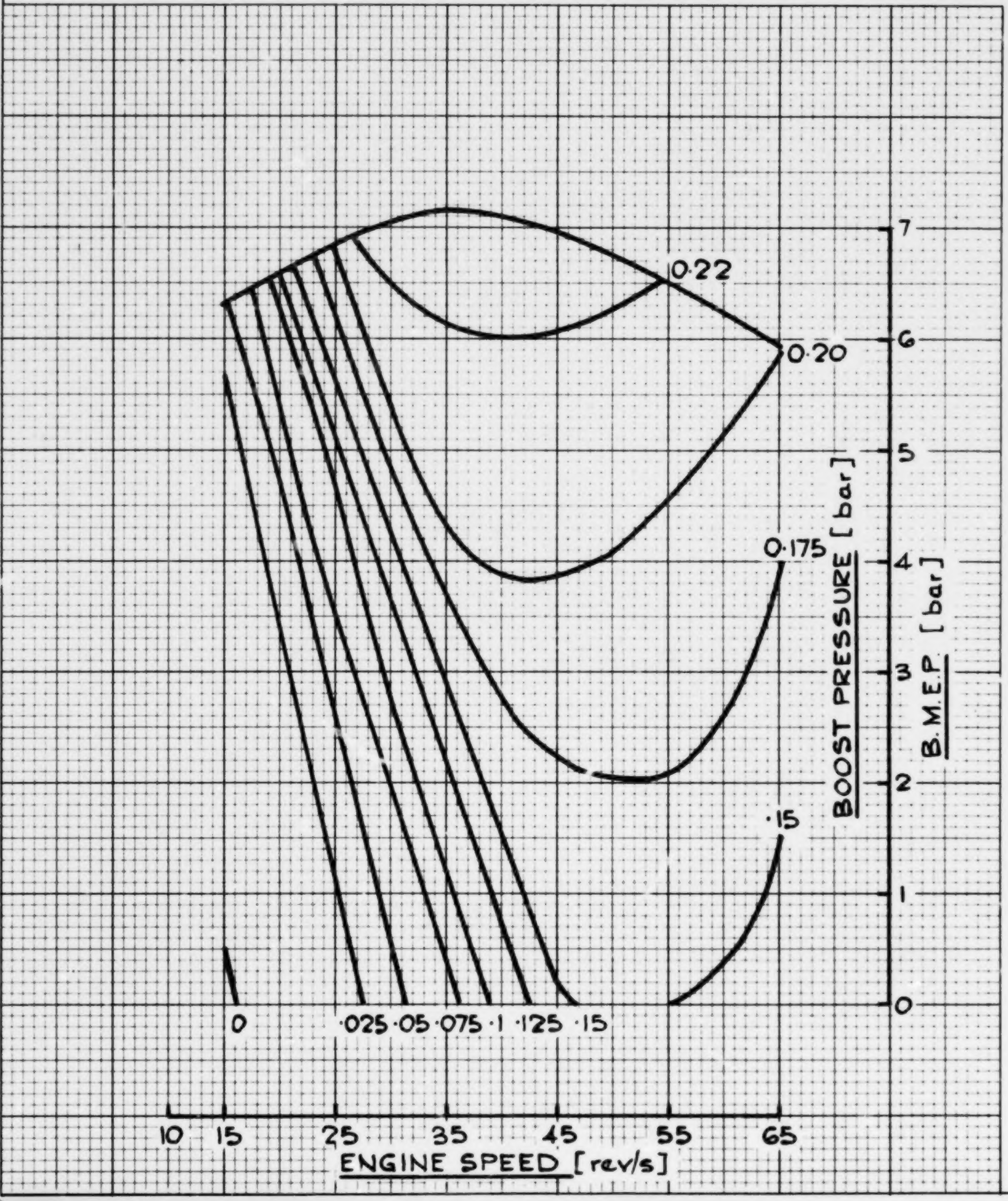


RICARDO CONSULTING ENGINEERS

FIG. No. 69
Drg. No. D34962
Date AUG.'77
Engine Curve 53

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.
COMPOSITE MAP OF TURBOCHARGER BOOST PRESSURE

TURBOCHARGED BUILD

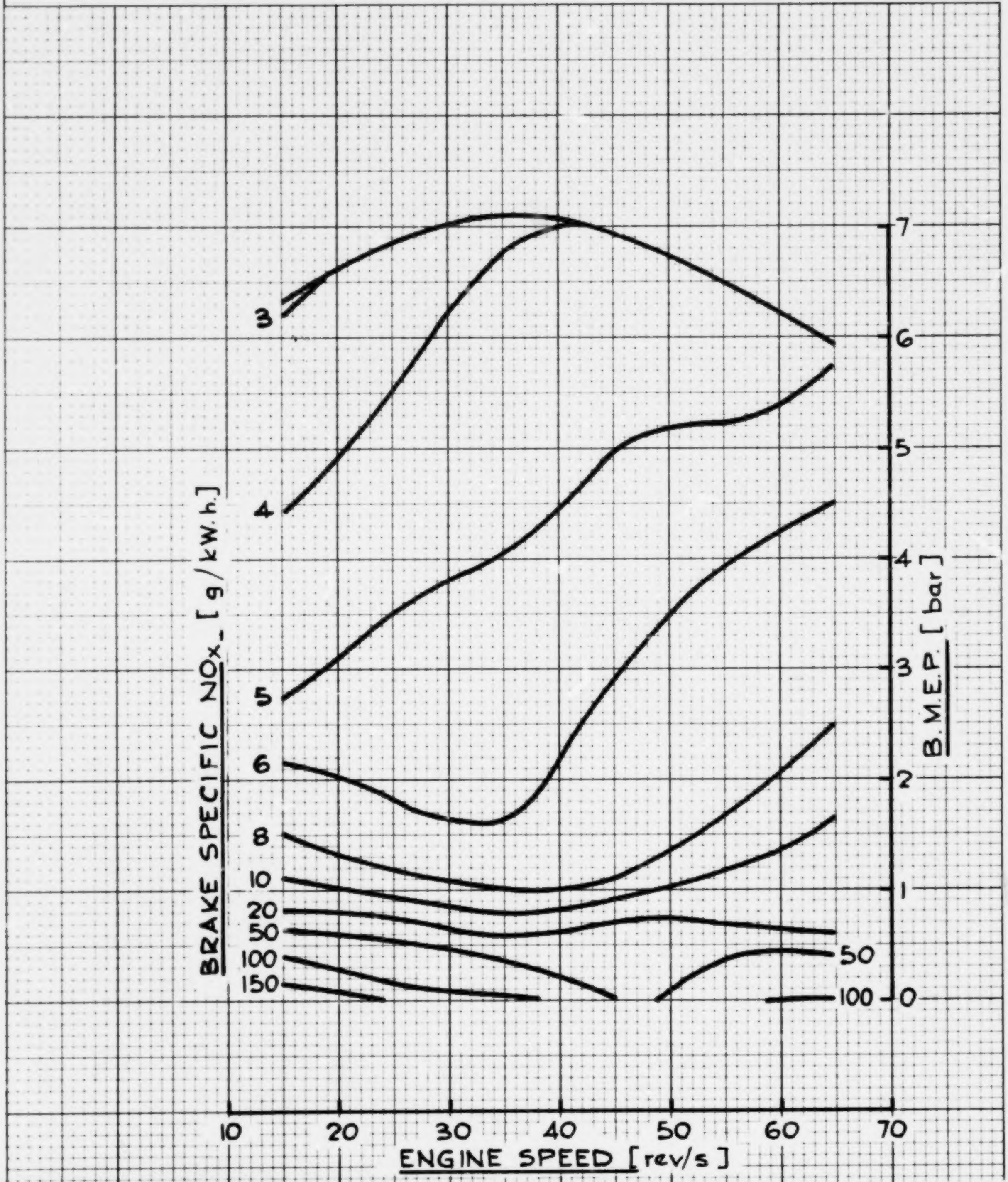


RICARDO CONSULTING ENGINEERS

FIG. No. 70
Drg. No. D34963
Date AUG. '77
Engine Curve 49A

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.
COMPOSITE MAP OF BRAKE SPECIFIC NOx EMISSION

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 71

Drg. No. D34964

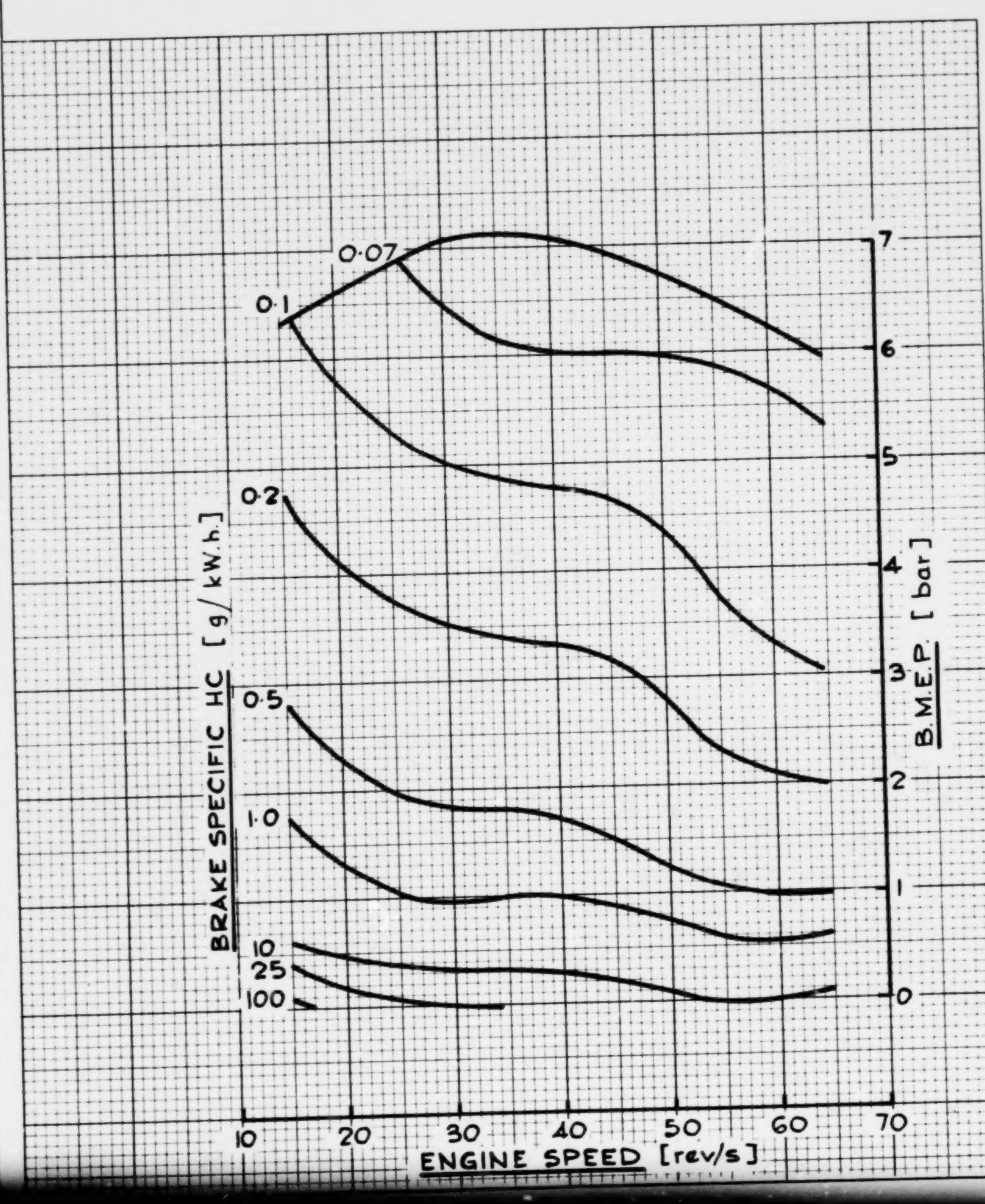
Date AUG. 77

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5CYL.

COMPOSITE MAP OF BRAKE SPECIFIC HC EMISSION

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 72

Drg. No. D34965

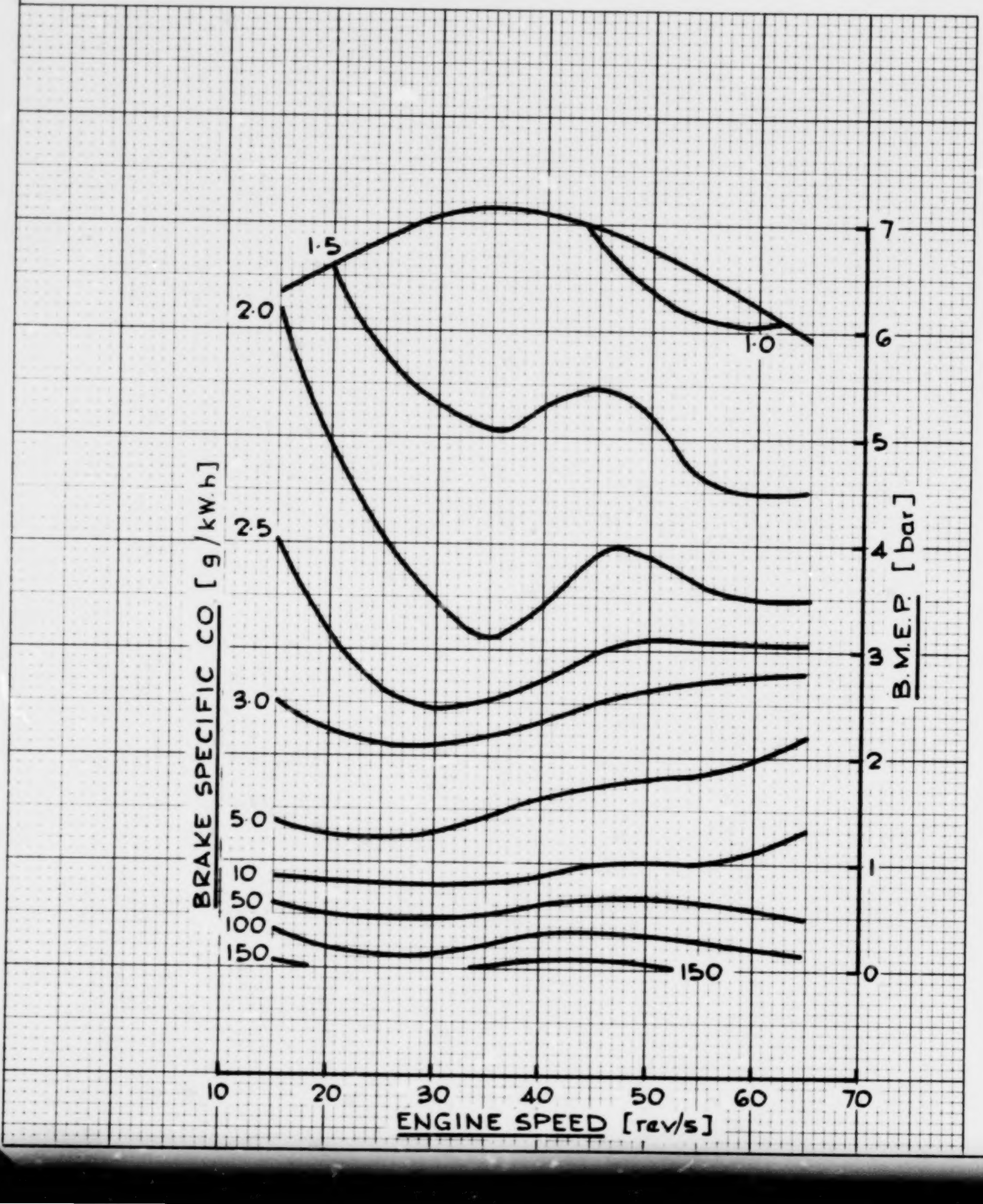
Date AUG.'77

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92·4mm x 5CYL.

COMPOSITE MAP OF BRAKE SPECIFIC CO EMISSION

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

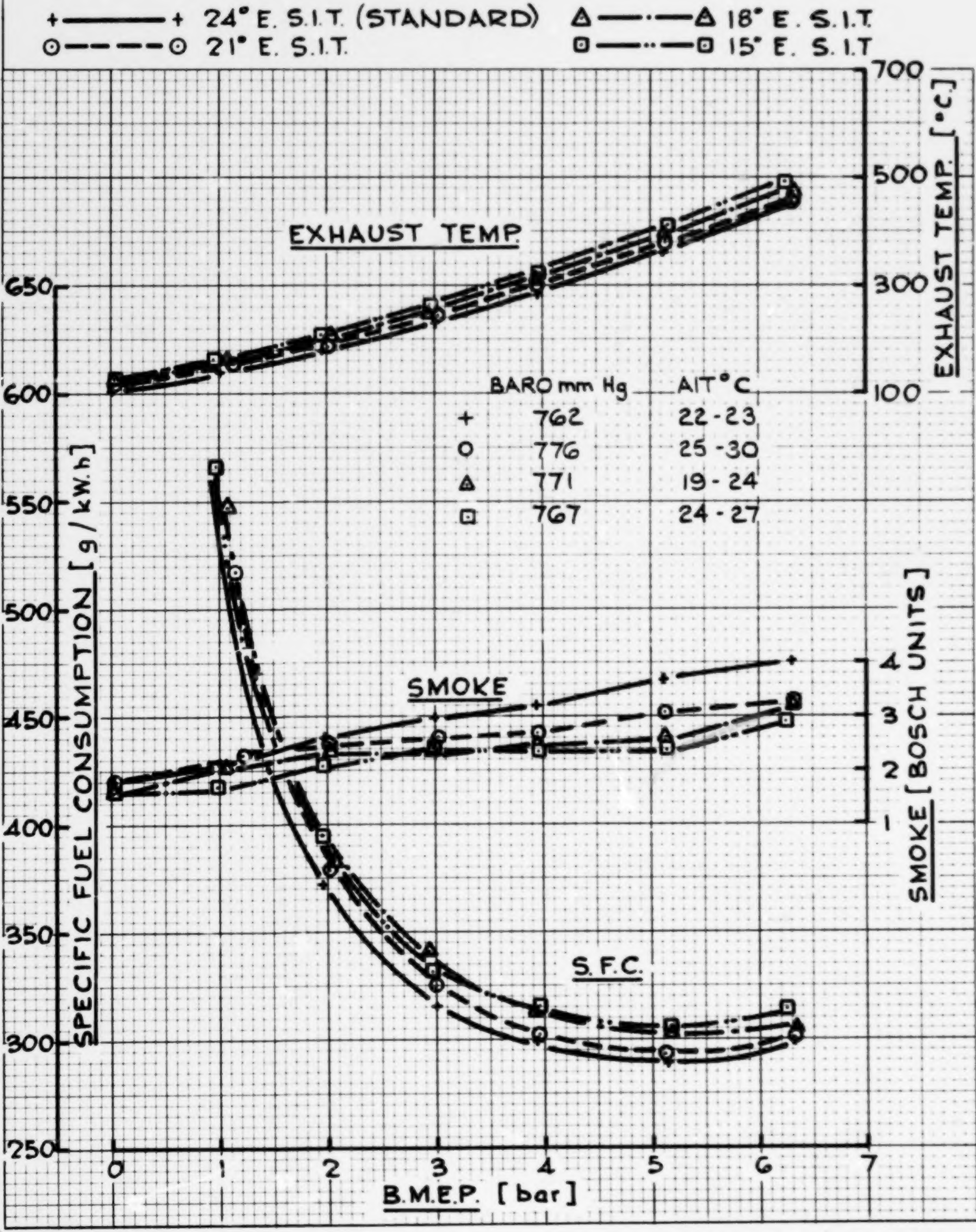
FIG. No. 73
Drg. No. D34966
Date SEPT '77
Engine Curve 57

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

LOAD RANGE PERFORMANCE AT VARIOUS INJECTION TIMINGS. 15 rev/s.

TURBOCHARGED BUILD



	BARO mm Hg	AIT °C
+	762	22 - 23
⊙	776	25 - 30
△	771	19 - 24
⊡	767	24 - 27

RICARDO CONSULTING ENGINEERS

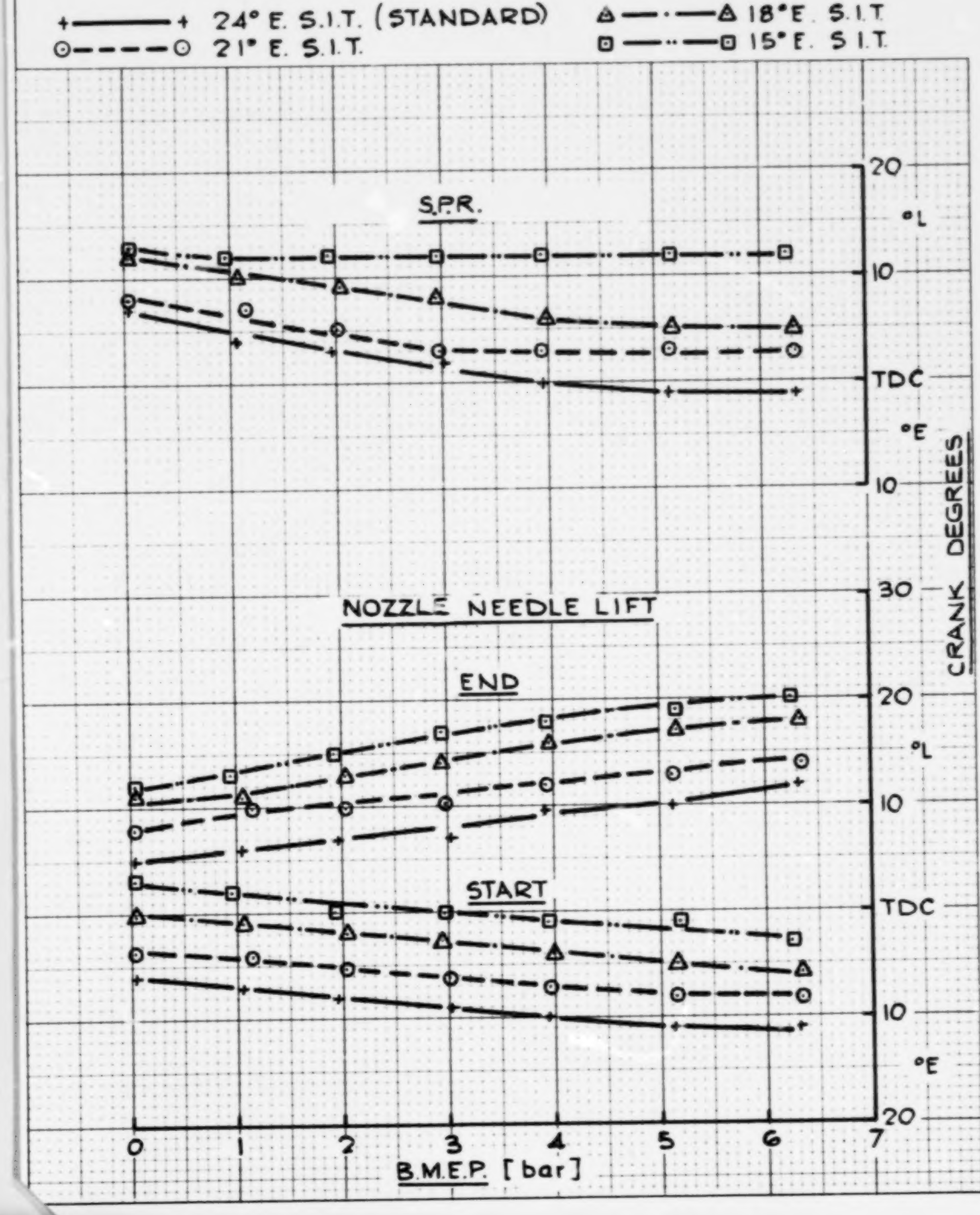
FIG. No. 74
Drg. No. D34967
Date SEPT '77
Engine Curve No. 59

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.

DYNAMIC NEEDLE LIFT AND START OF PRESSURE RISE AT 15 rev/s - VARIOUS INJECTION TIMINGS

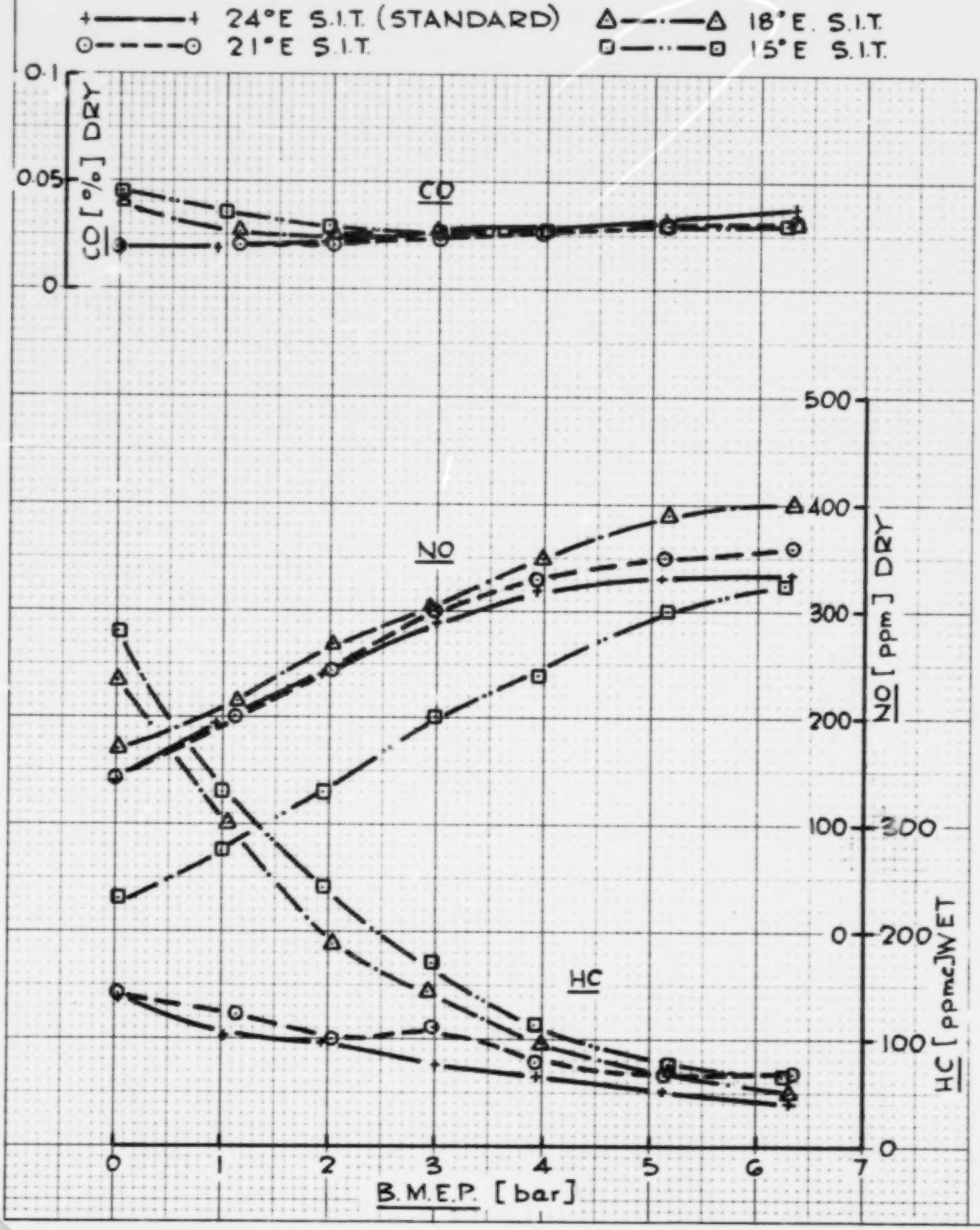
TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 75
Drg. No. D34968
Date SEPT '77
Engine Curve 58

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
HC, NO, AND CO EMISSIONS AT VARIOUS INJECTION TIMINGS 15 rev/s.
TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 76

Drg. No. D34969

Date SEPT.'77

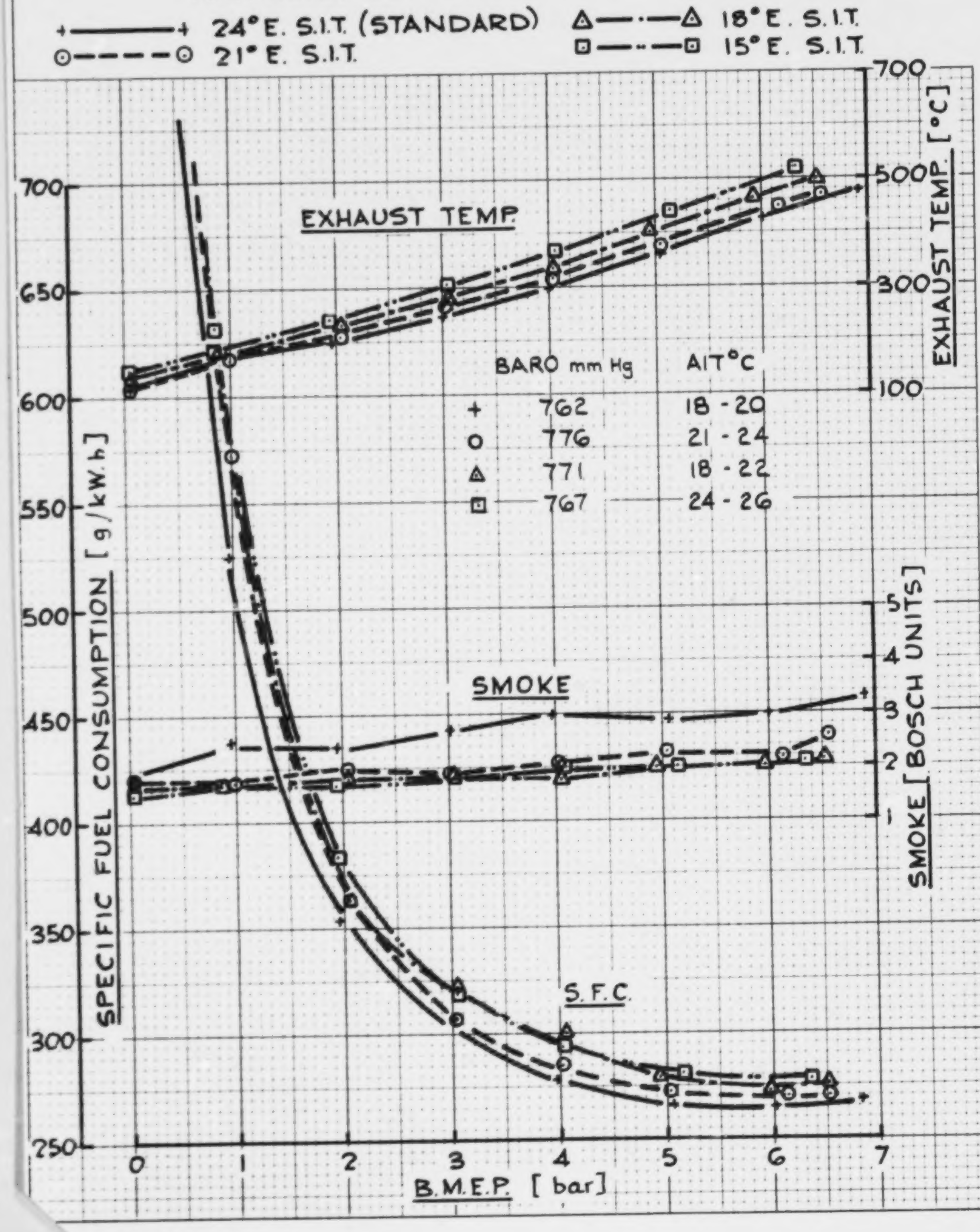
Engine Curve 60

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92·4mm x 5CYL.

LOAD RANGE PERFORMANCE AT VARIOUS INJECTION TIMINGS: 25 rev/s.

TURBOCHARGED BUILD



	BARO mm Hg	AIT°C
+	762	18 - 20
o	776	21 - 24
△	771	18 - 22
⊡	767	24 - 26

RICARDO CONSULTING ENGINEERS

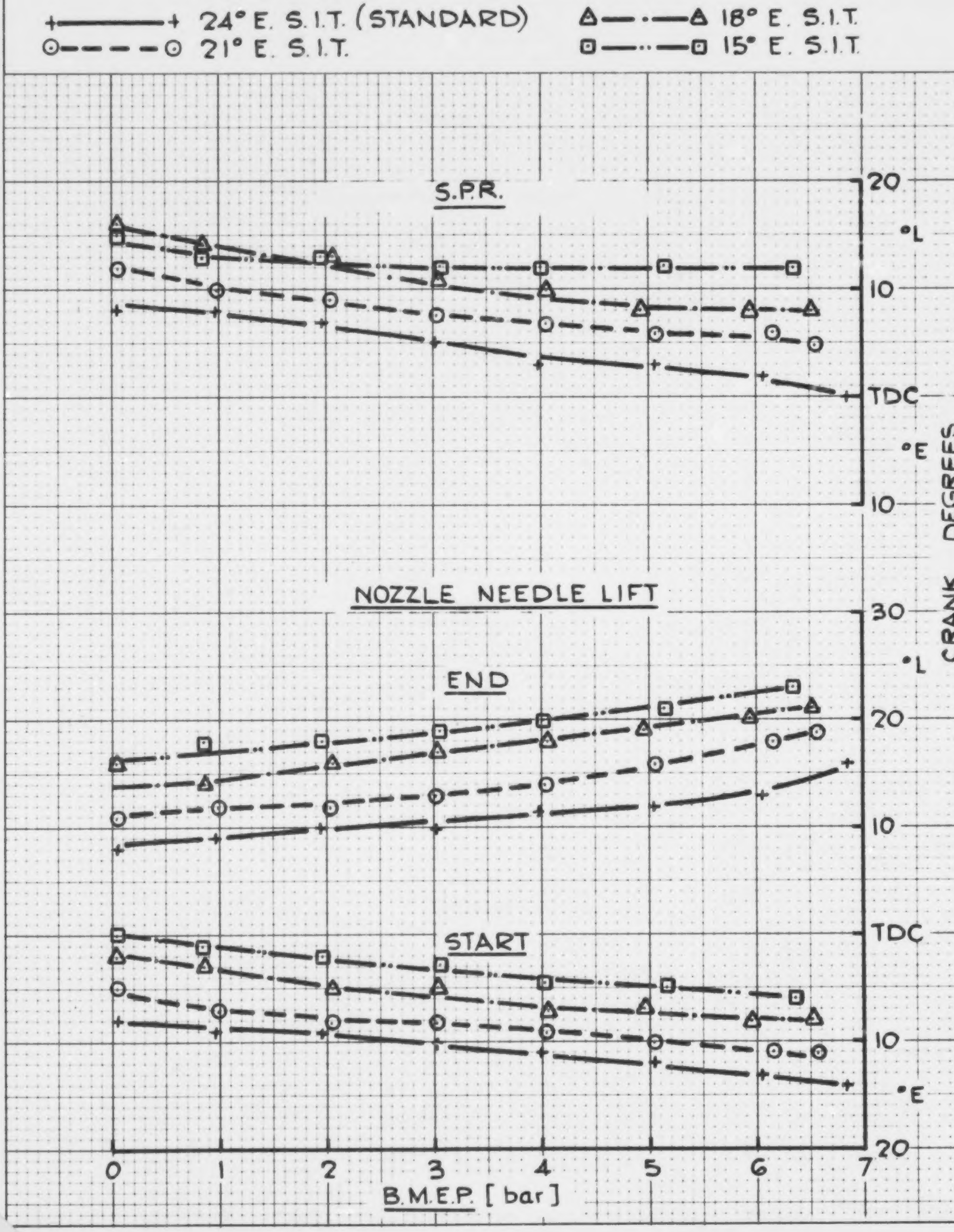
FIG. No. 77
Drg. No. D34970
Date SEPT '77
Engine Curve No. 62

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm × 92.4 mm × 5 CYL.

DYNAMIC NEEDLE LIFT AND START OF PRESSURE RISE AT 25 rev/s. - VARIOUS INJECTION TIMINGS

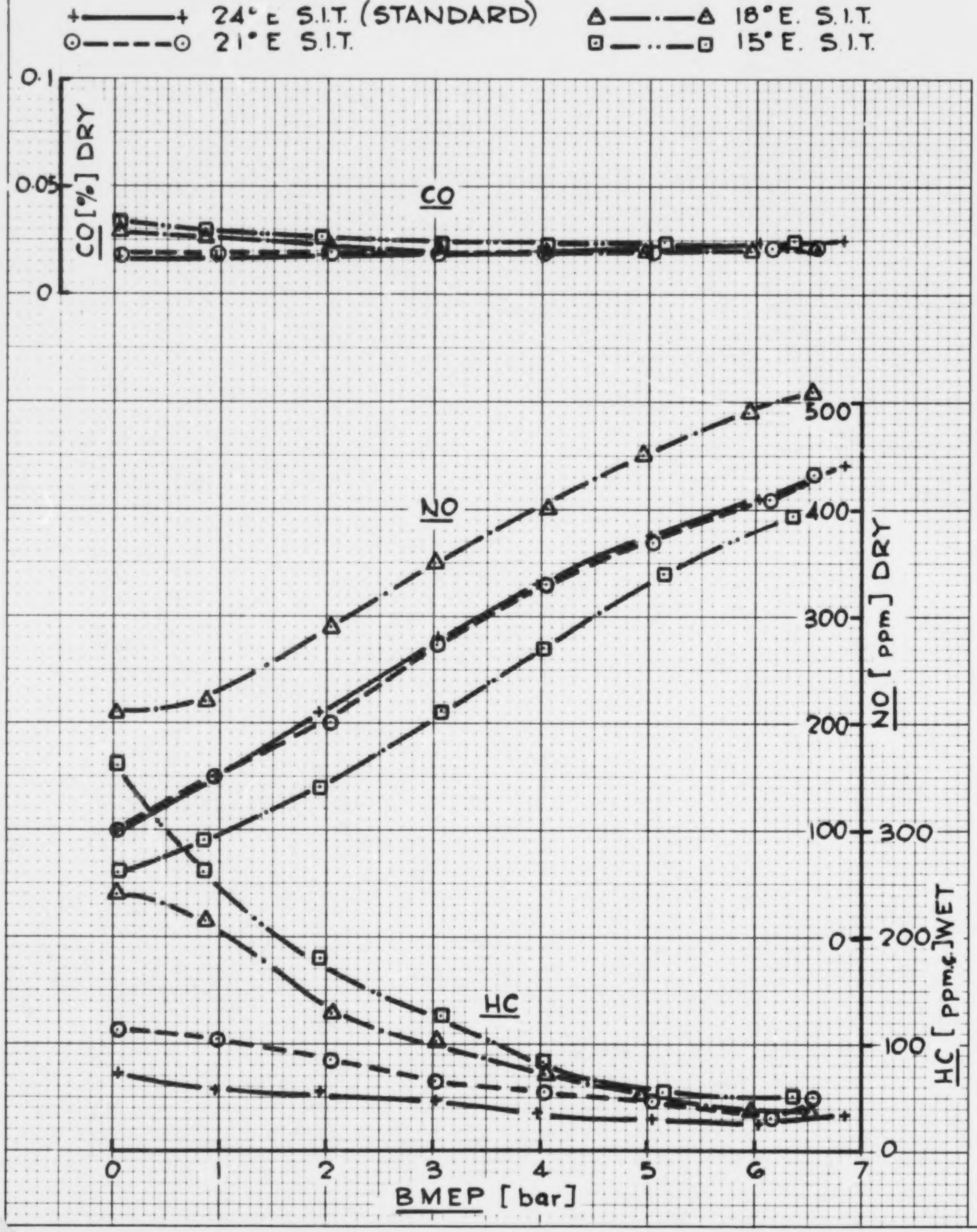
TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 78
Drg. No. D34971
Date SEPT.'77
Engine Curve No. 61

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92.4 mm x 5 CYL.
HC, NO AND CO EMISSIONS AT VARIOUS INJECTION TIMINGS 25 rev/s.
TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

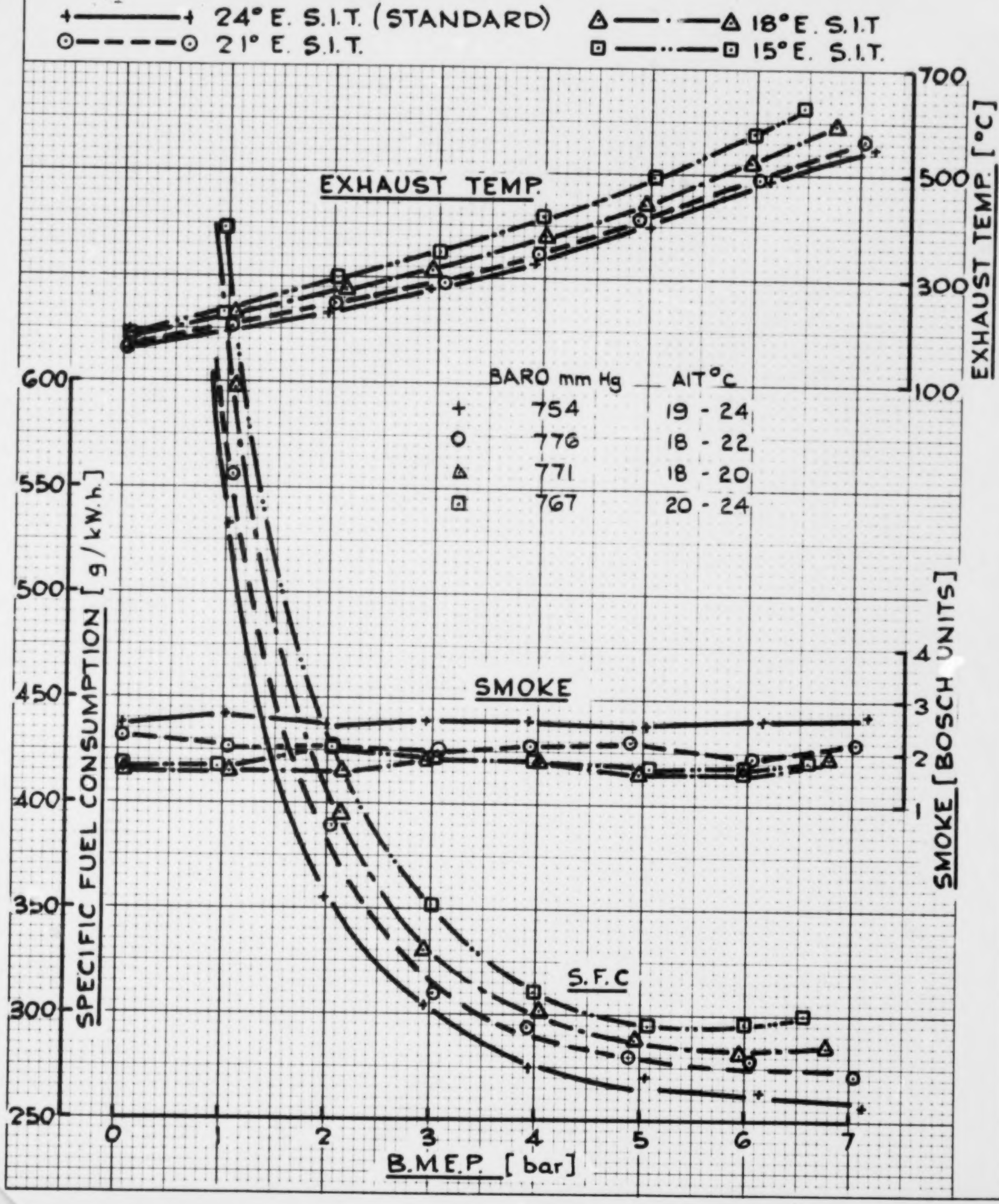
FIG. No. 79
Drg. No. D34972
Date SEPT' 77
Engine Curve 63

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm × 92·4 mm × 5 CYL.

LOAD RANGE PERFORMANCE AT VARIOUS INJECTION TIMINGS : 35 rev/s.

TURBOCHARGED BUILD



	BARO mm Hg	AIT °C
+	754	19 - 24
○	776	18 - 22
△	771	18 - 20
⊡	767	20 - 24

RICARDO CONSULTING ENGINEERS

FIG. No. 80
Drg. No. D34973
Date SEPT. '77
Engine Curve No. 65

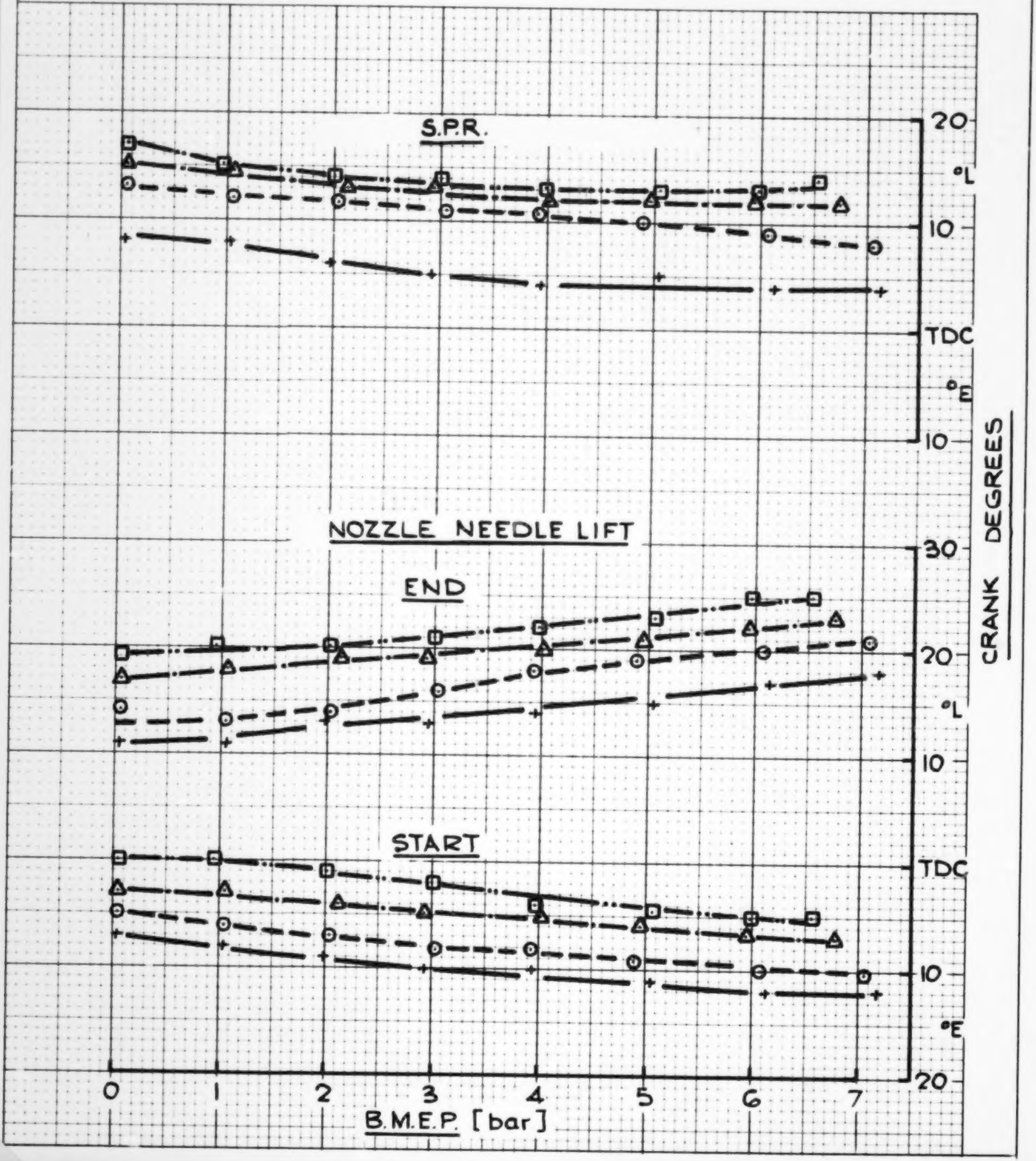
EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5 CYL.

DYNAMIC NEEDLE LIFT AND START OF PRESSURE RISE AT 35 rev/s - VARIOUS INJECTION TIMINGS.

TURBOCHARGED BUILD

+———+ 24° E. S.I.T. (STANDARD)
⊙- - - -⊙ 21° E. S.I.T.
△—·—△ 18° E. S.I.T.
⊡—··—⊡ 15° E. S.I.T.



RICARDO CONSULTING ENGINEERS

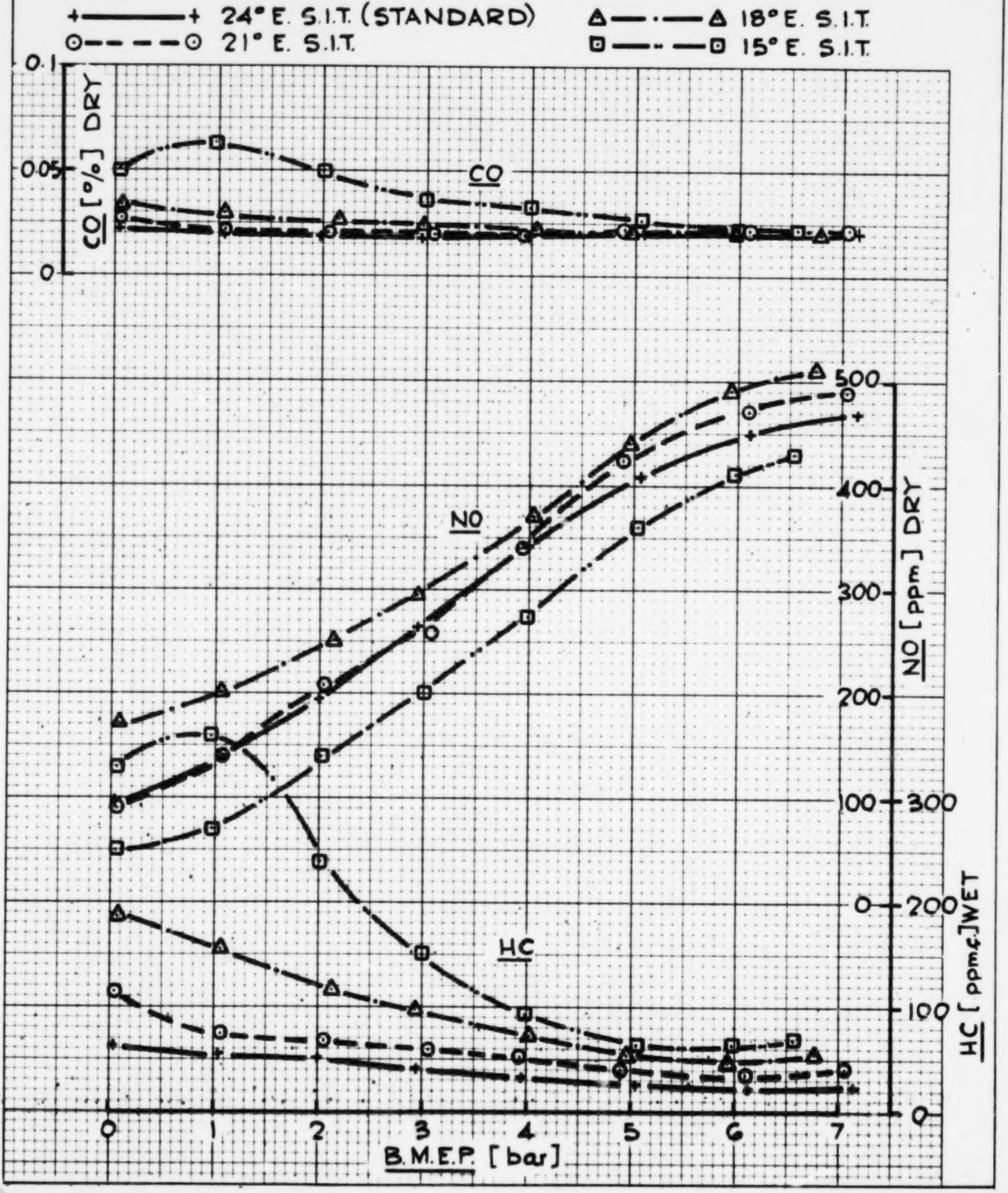
FIG. No. 81
Drg. No. D34974
Date SEPT. '77
Engine Curve No. 64

EPA MODULATED EGR STUDY

MERCEDES OMG17 ENGINE 91 mm x 92·4 mm x 5 CYL.

HC, NO AND CO EMISSIONS AT VARIOUS INJECTION TIMINGS 35 rev/s

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

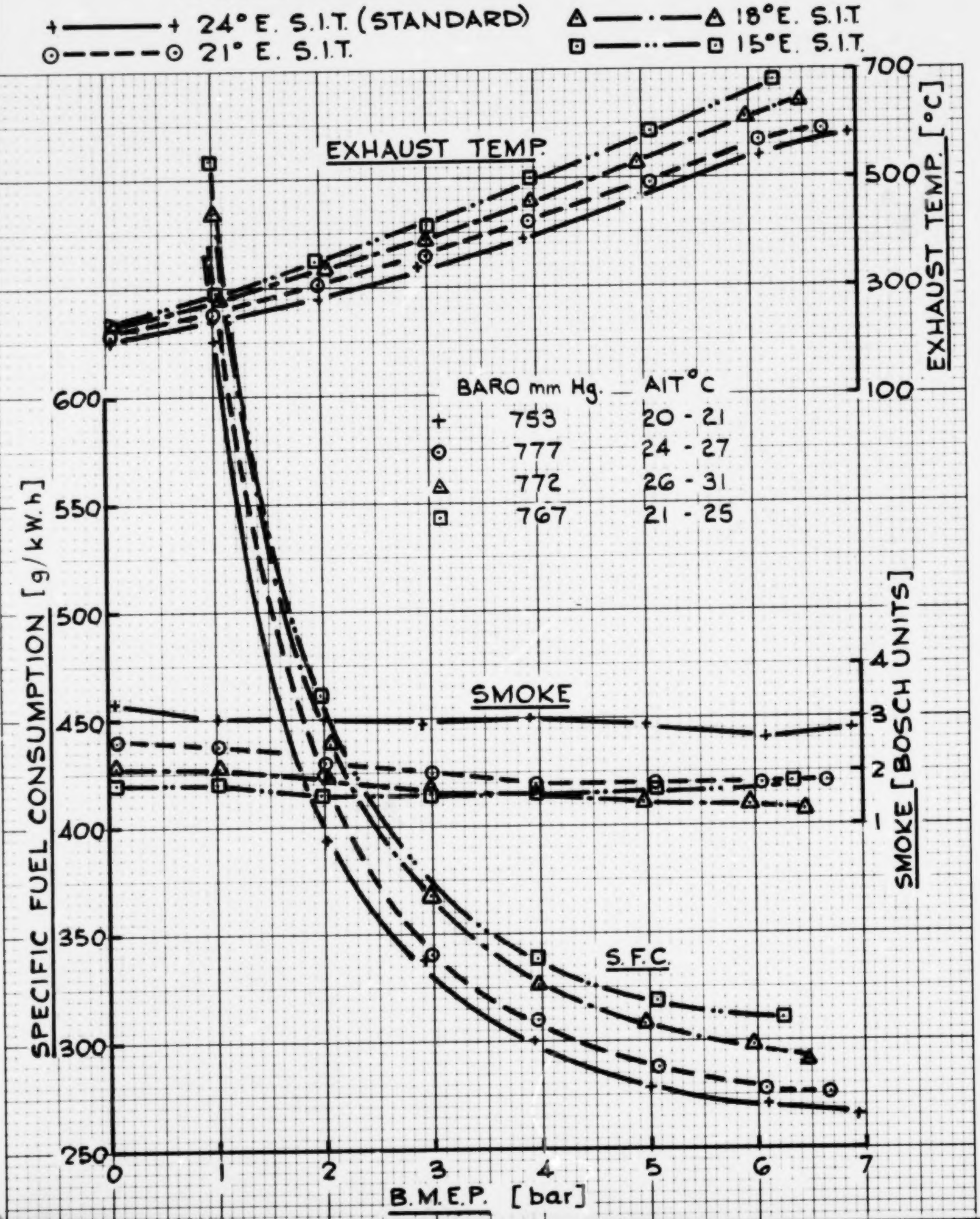
FIG. No. 82
Drg. No. D34975
Date SEPT.'77
Engine Curve 86

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5 CYL.

LOAD RANGE PERFORMANCE AT VARIOUS INJECTION TIMINGS - 45 rev/s

TURBOCHARGED BUILD



	BARO mm Hg.	AIT °C
+	753	20 - 21
⊙	777	24 - 27
△	772	26 - 31
⊡	767	21 - 25

RICARDO CONSULTING ENGINEERS

FIG. No. 83

Drg. No. D34976

Date SEPT. '77

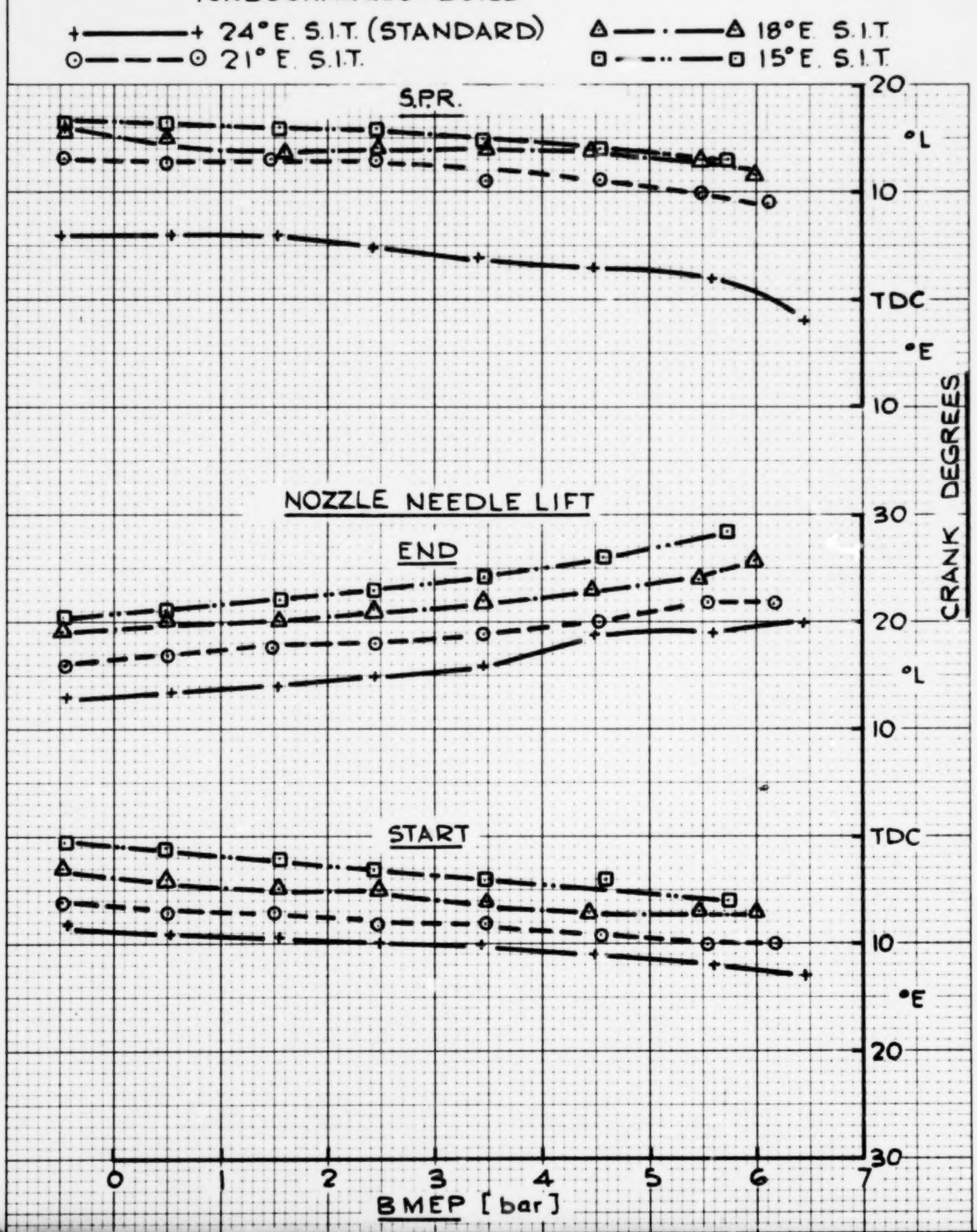
Engine Curve No. 68

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

DYNAMIC NEEDLE LIFT AND START OF PRESSURE RISE AT 45 rev/s - VARIOUS INJECTION TIMINGS

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

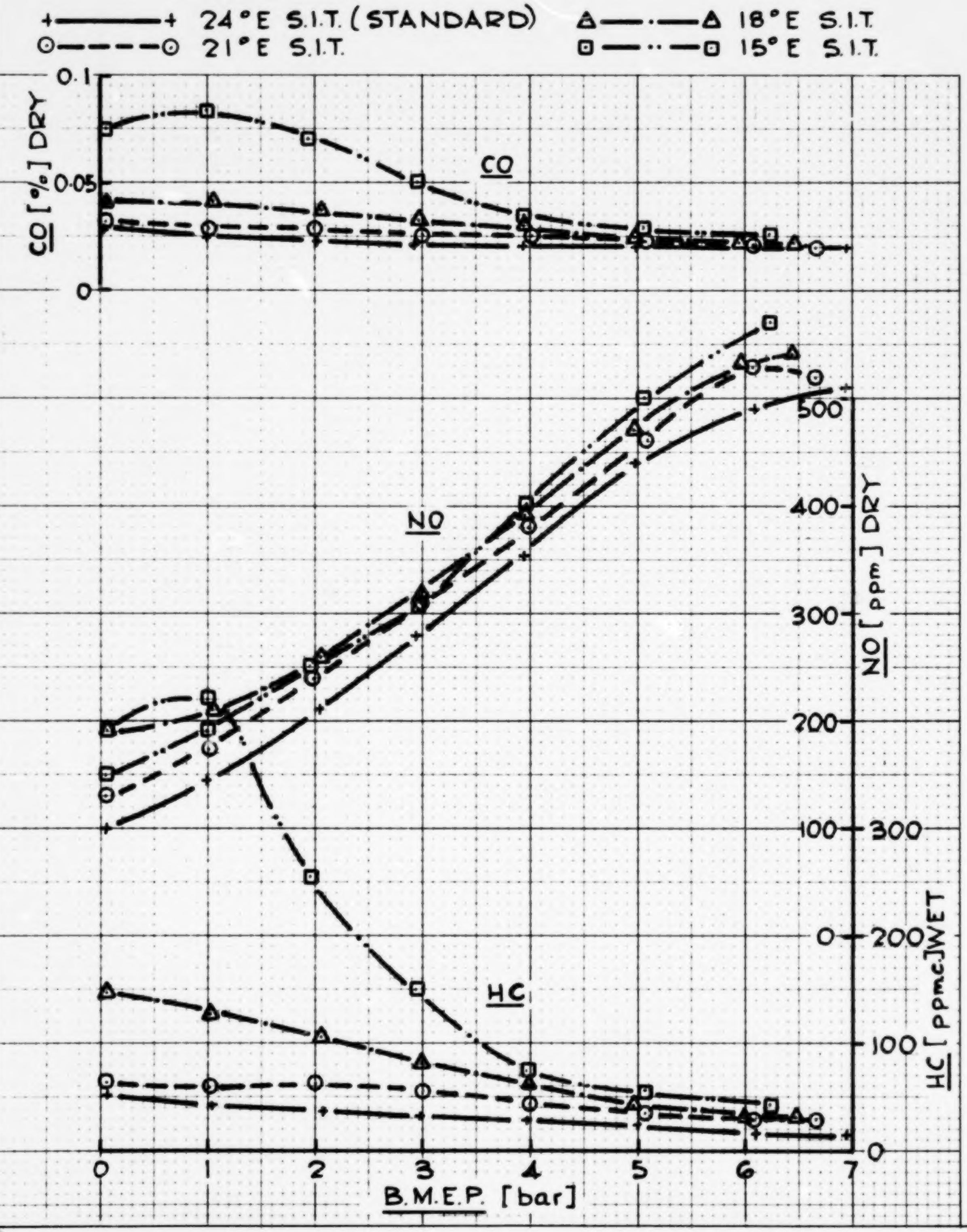
FIG. No. 84
Drg. No. D34977
Date SEPT '77
Engine Curve 67

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92.4 mm x 5 CYL.

HC, NO AND CO EMISSIONS AT VARIOUS INJECTION TIMINGS 45 rev/s.

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG No. 85
Drg. No. D34978
Date SEPT'77
Engine Curve 69

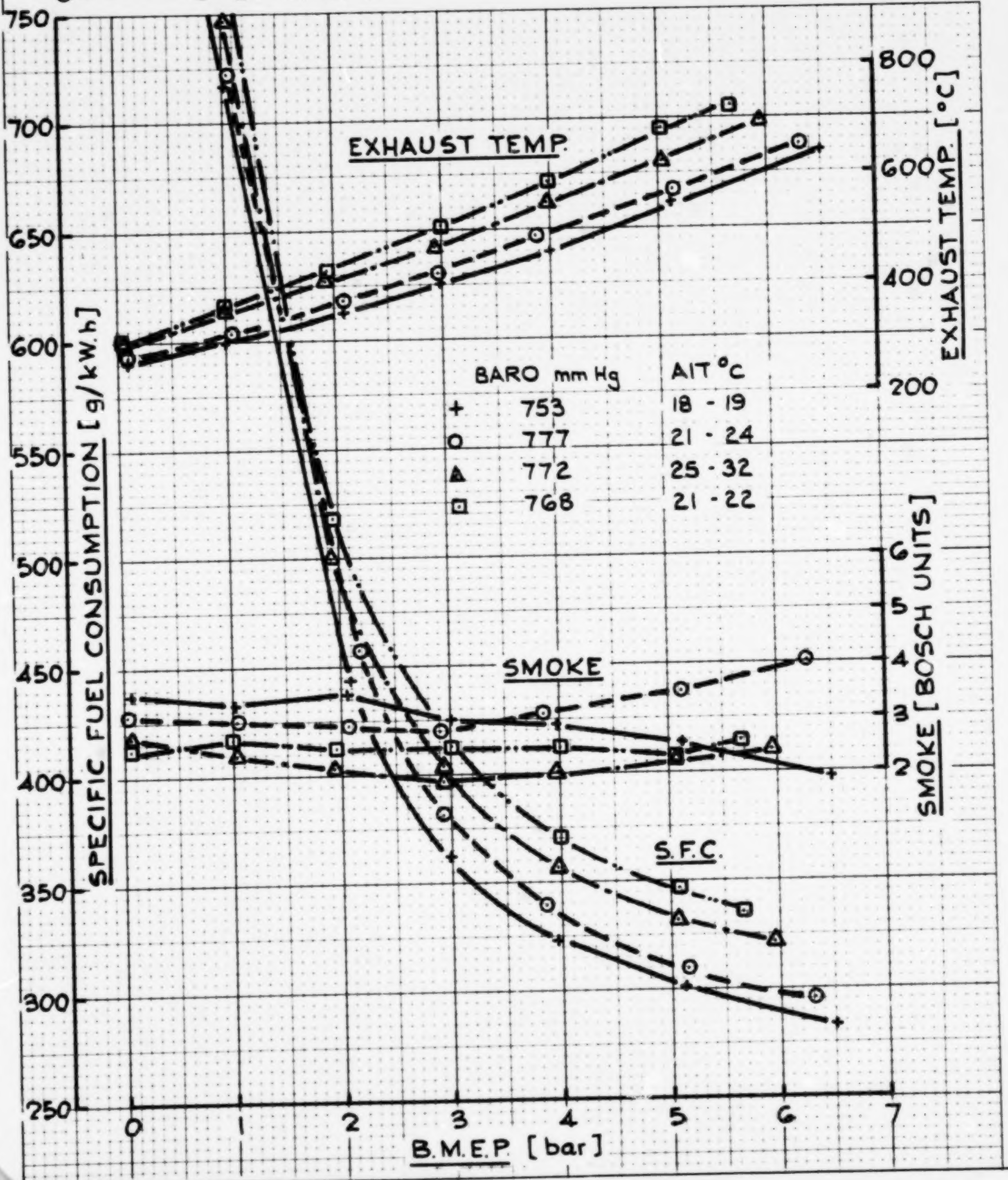
EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.

LOAD RANGE PERFORMANCE AT VARIOUS INJECTION TIMINGS : 55 rev/s

TURBOCHARGED BUILD

+ ——— + 24° E. S.I.T. (STANDARD)
⊙ – – – ⊙ 21° E. S.I.T.
△ —·— △ 18° E. S.I.T.
⊡ —··— ⊡ 15° E. S.I.T.



RICARDO CONSULTING ENGINEERS

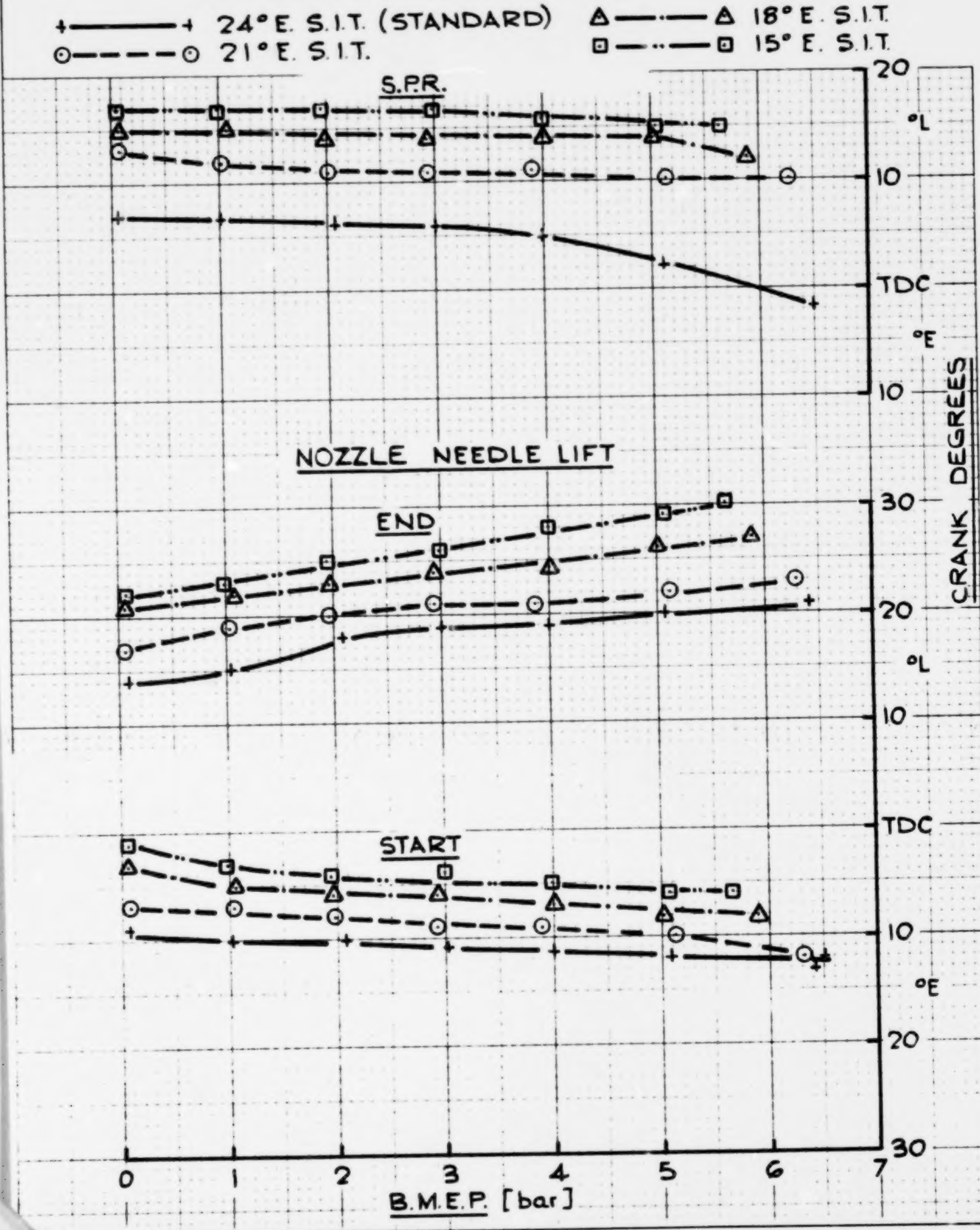
FIG. No. 86
Drg. No. D34979
Date SEPT. '77
Engine Curve No. 71

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm × 92.4 mm × 5 CYL.

DYNAMIC NEEDLE LIFT AND START OF PRESSURE RISE AT 55 rev/s - VARIOUS INJECTION TIMINGS

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

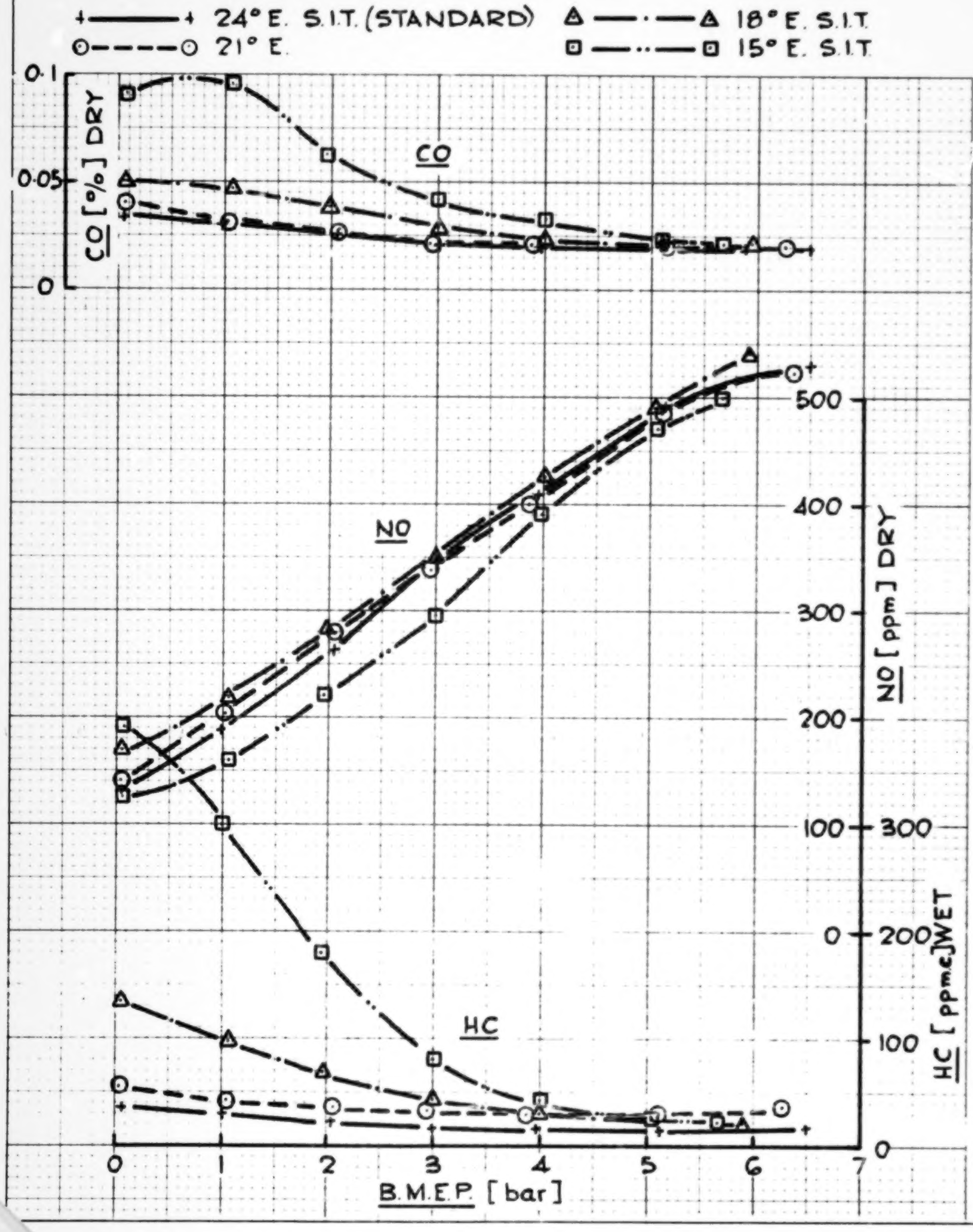
FIG. No. 87
Drg. No. D34980
Date SEPT '77
Engine Curve 70

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92·4mm x 5CYL.

HC, NO AND CO EMISSIONS AT VARIOUS INJECTION TIMINGS: 55 rev/s.

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

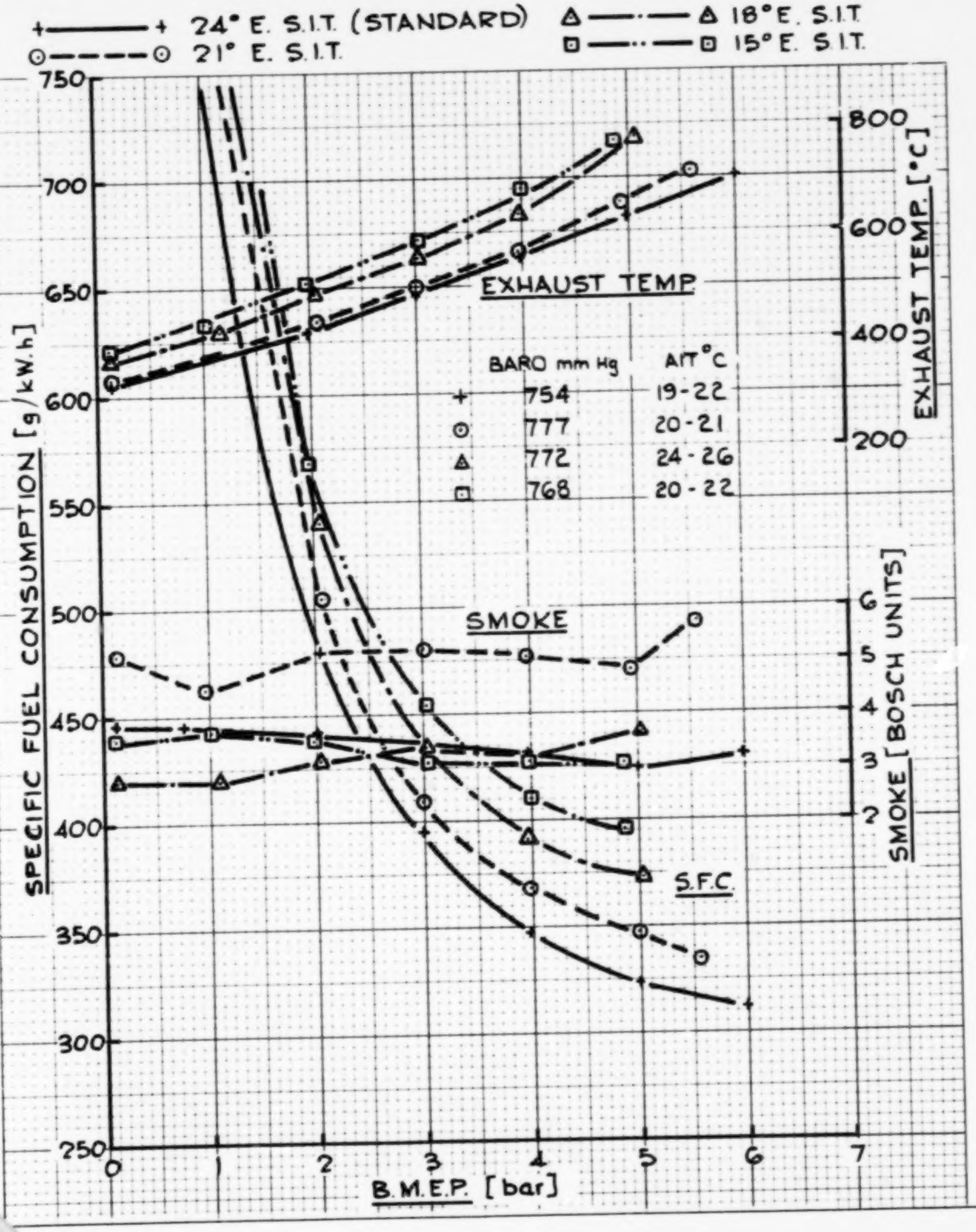
FIG. No. 88
Drg. No. D34981
Date SEPT. '77
Engine Curve No. 72

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92.4 mm x 5 CYL.

LOAD RANGE PERFORMANCE AT VARIOUS INJECTION TIMINGS: 65 rev/s

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

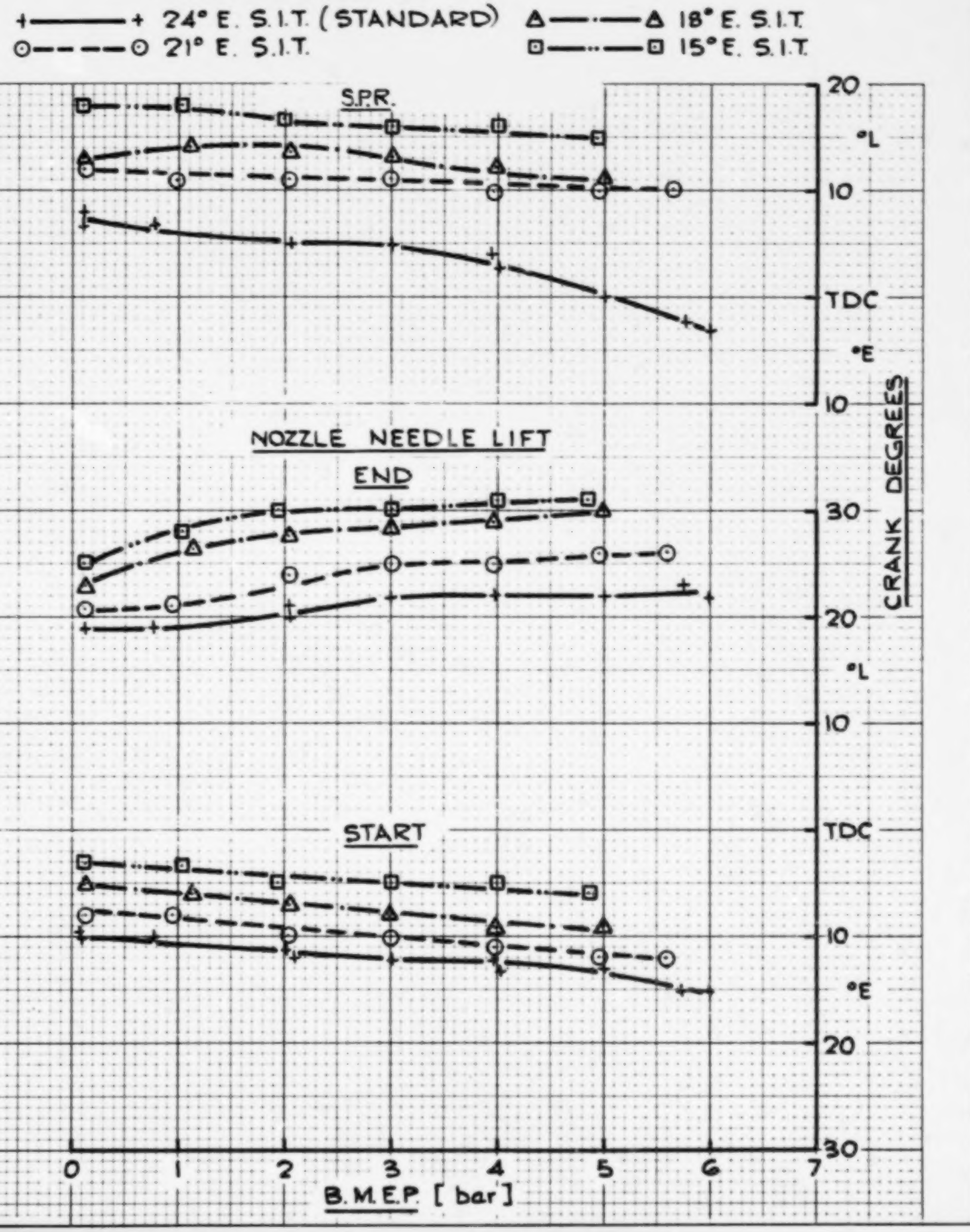
FIG. No. 89
Drg. No. D34982
Date SEPT '77
Engine Curve '74

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

DYNAMIC NEEDLE LIFT AND START OF PRESSURE RISE AT 65 rev/s. - VARIOUS INJECTION TIMINGS

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 90
Drg. No. D34983
Date SEPT. '77
Engine Curve No. 73

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
HC, NO AND CO EMISSIONS AT VARIOUS INJECTION TIMINGS: 65 rev/s.
TURBOCHARGED BUILD

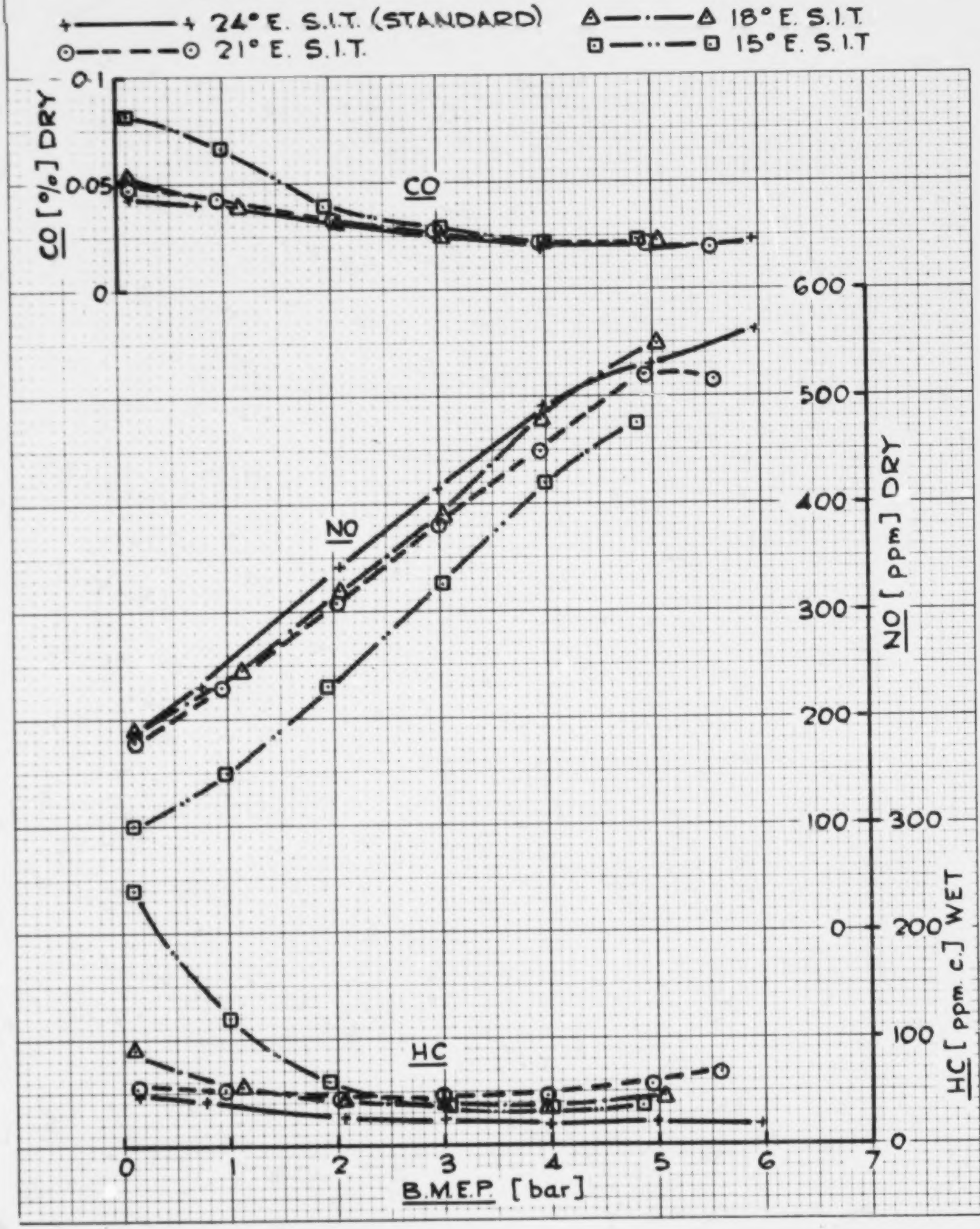
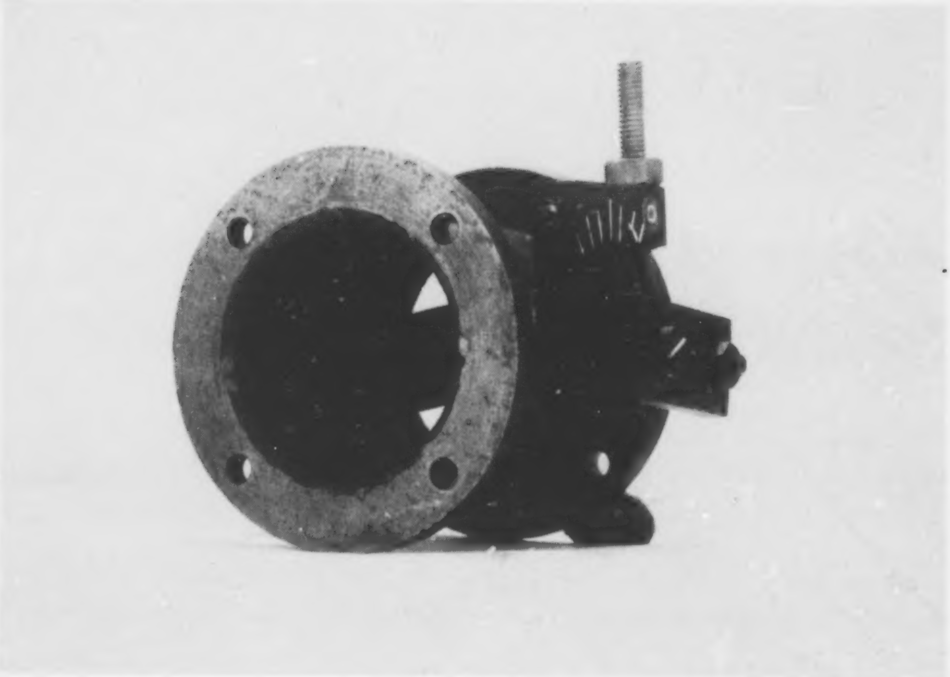


FIGURE 91



EGR Butterfly Valve

RICARDO CONSULTING ENGINEERS

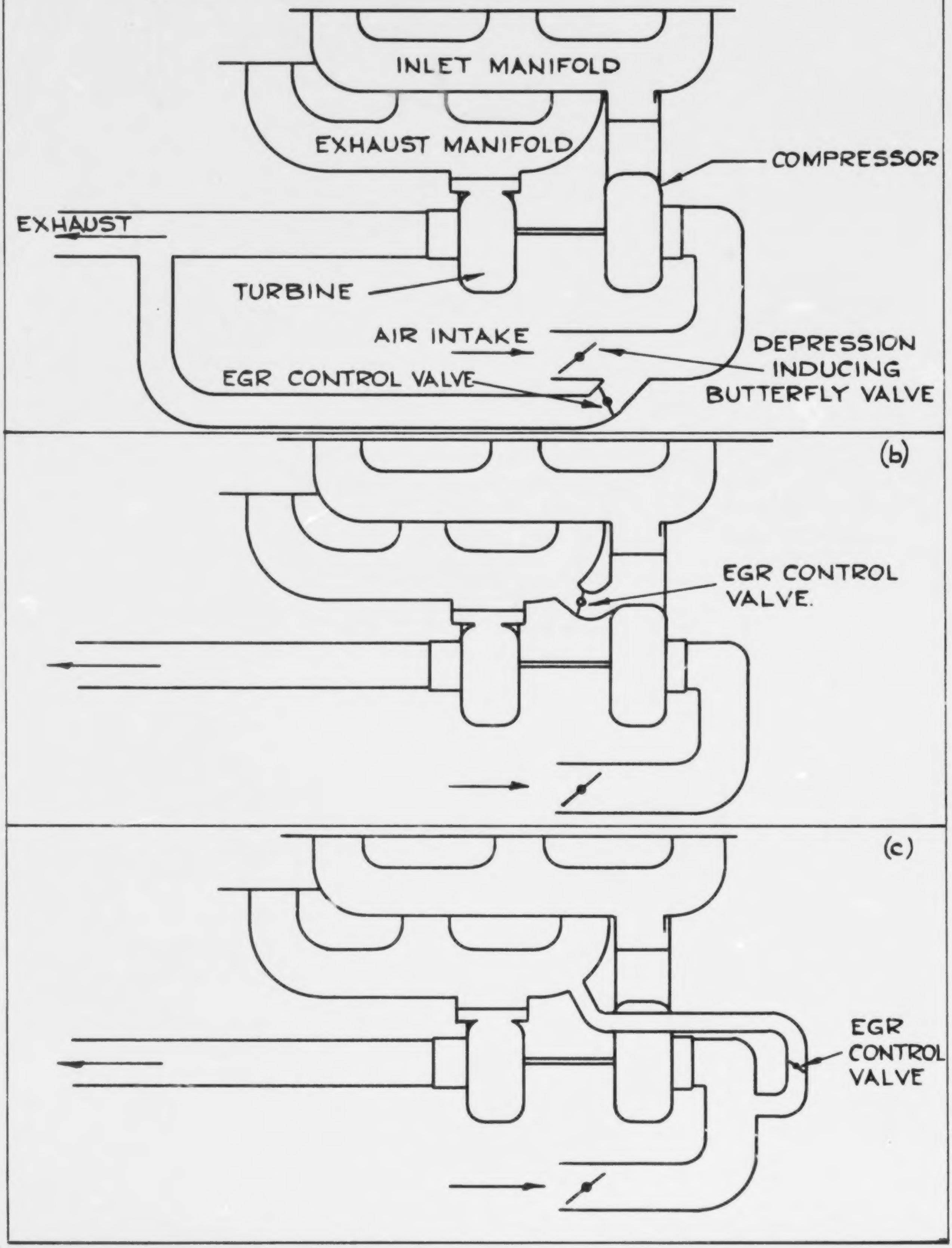
EPA MODULATED EGR STUDY

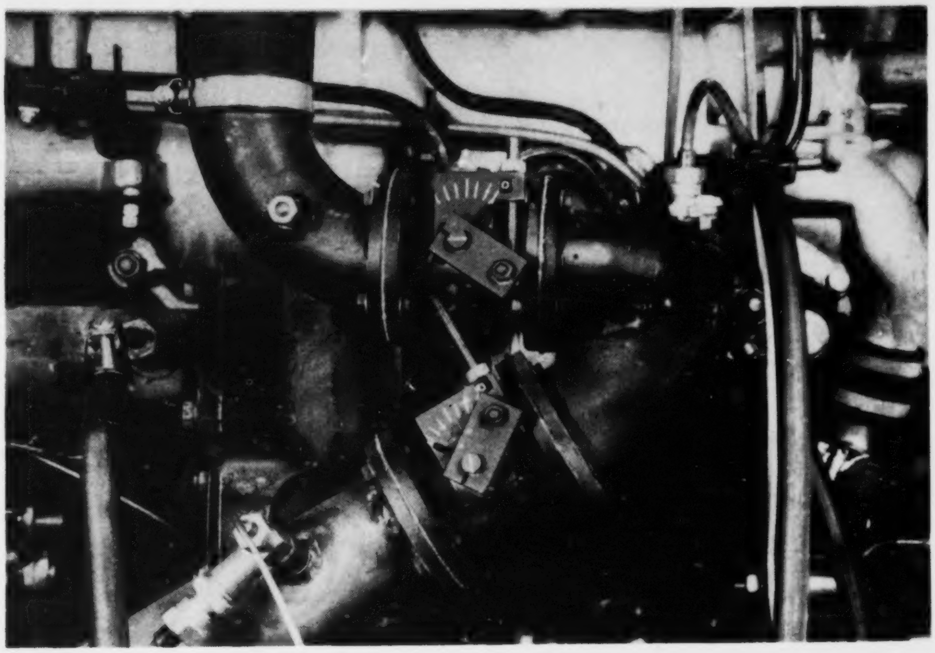
ALTERNATIVE EGR CIRCUITS

FIG. No. 92 (a)

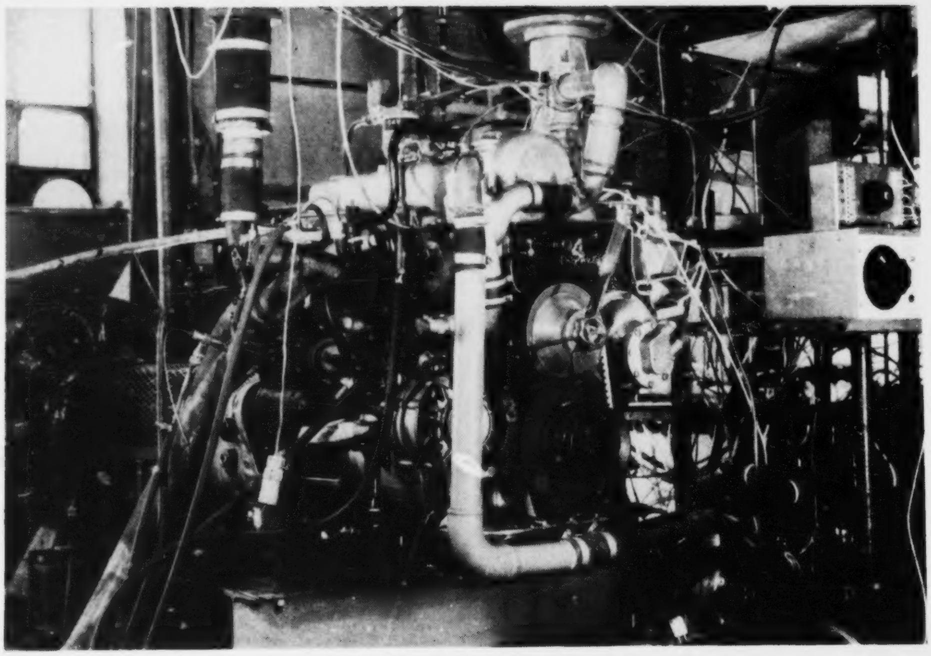
DRG. No. D34984

DATE :- OCT. '77


INLET MANIFOLD
EXHAUST MANIFOLD
COMPRESSOR
EXHAUST
TURBINE
AIR INTAKE
DEPRESSION INDUCING BUTTERFLY VALVE
EGR CONTROL VALVE
(b)
EGR CONTROL VALVE.
(c)
EGR CONTROL VALVE



a. Mk I EGR Valve Installation



b. Test Bed Installation

RICARDO CONSULTING ENGINEERS

FIG. No. 94

Drg. No. D34985

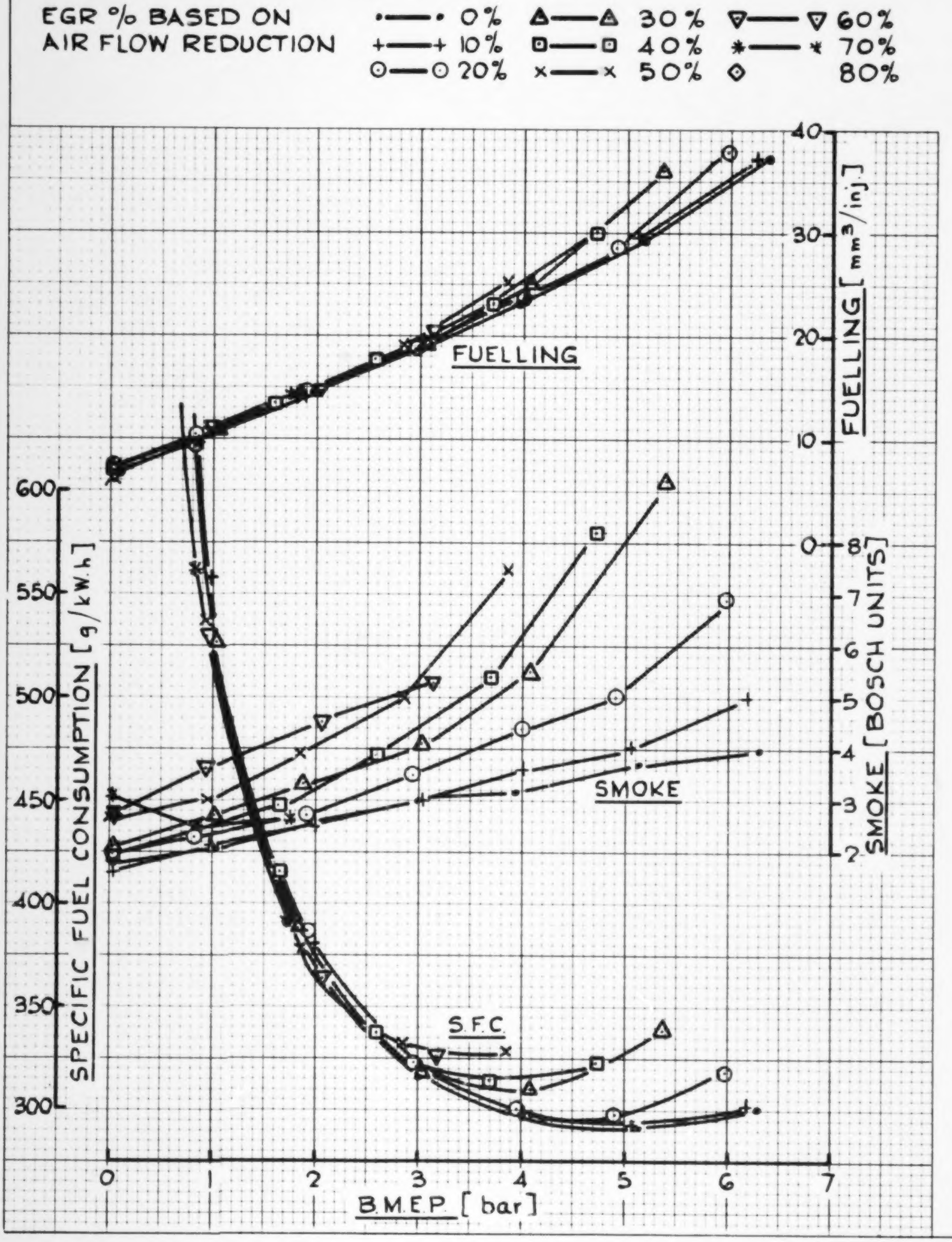
Date OCT/NOV '77

Engine Curve 75

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm × 92·4 mm × 5 CYL.

CURVES SHOWING EFFECT OF EGR ON PERFORMANCE AT 15 rev/s. - TURBOCHARGED BUILD.



RICARDO CONSULTING ENGINEERS

FIG. No. 95

Drg. No. D34986

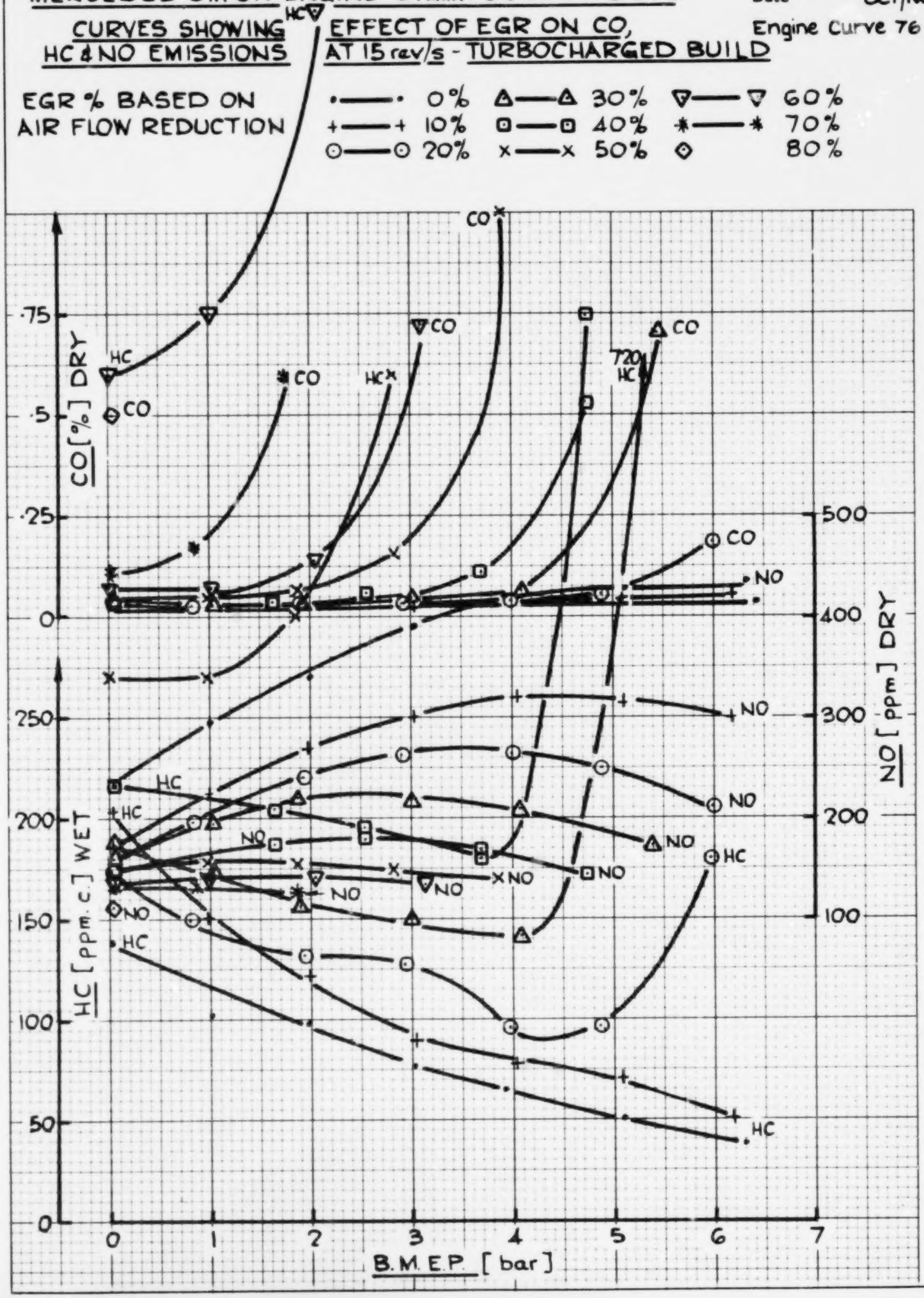
Date OCT/NOV '77

Engine Curve 76

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5 CYL.

CURVES SHOWING EFFECT OF EGR ON CO, HC & NO EMISSIONS AT 15 rev/s - TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 96

Drg. No. D34987

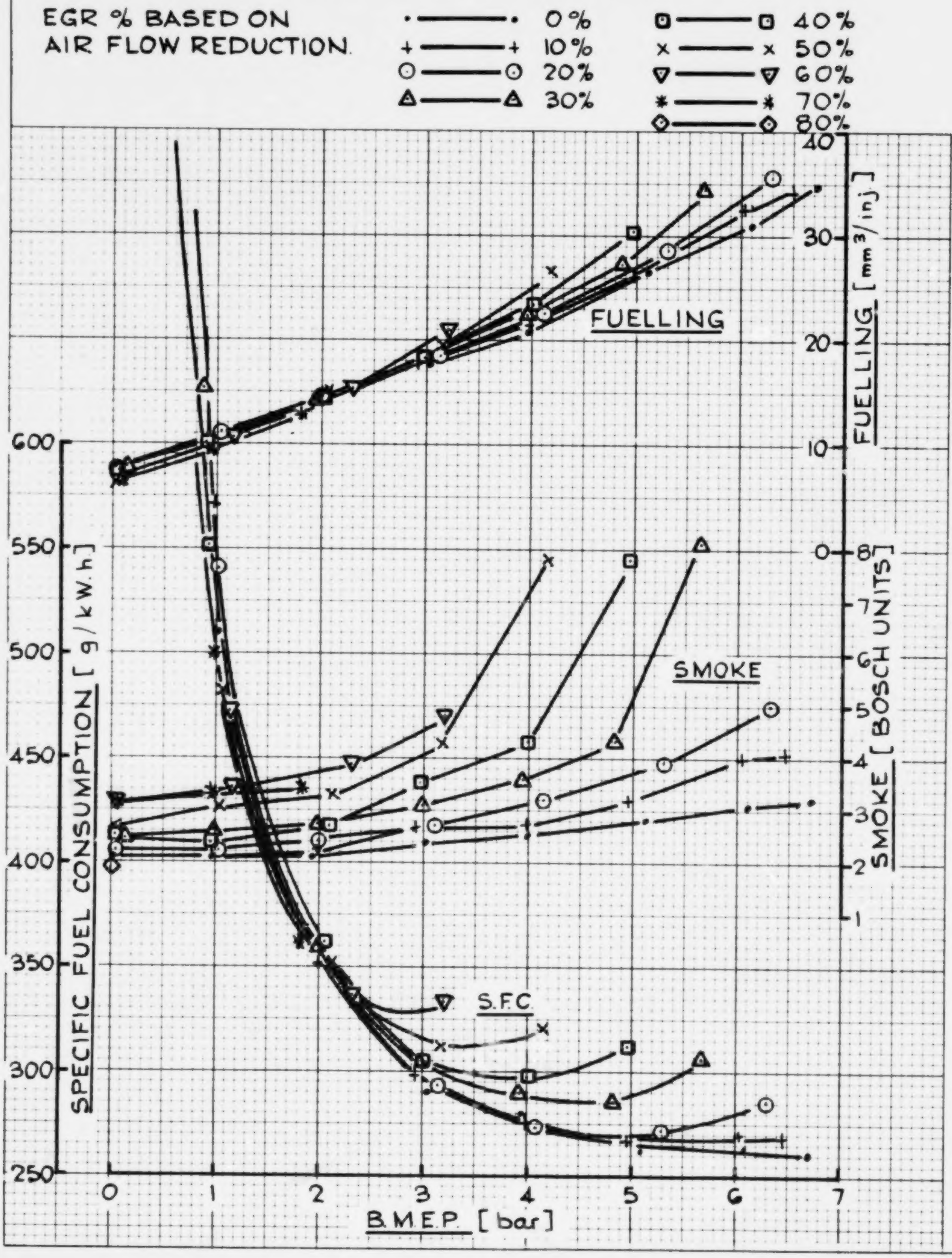
Date OCT/NOV '77

Engine Curve 77

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5CYL.

CURVES SHOWING EFFECT OF EGR ON ENGINE PERFORMANCE AT 25 rev/s – TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 97

Drg. No. D34988

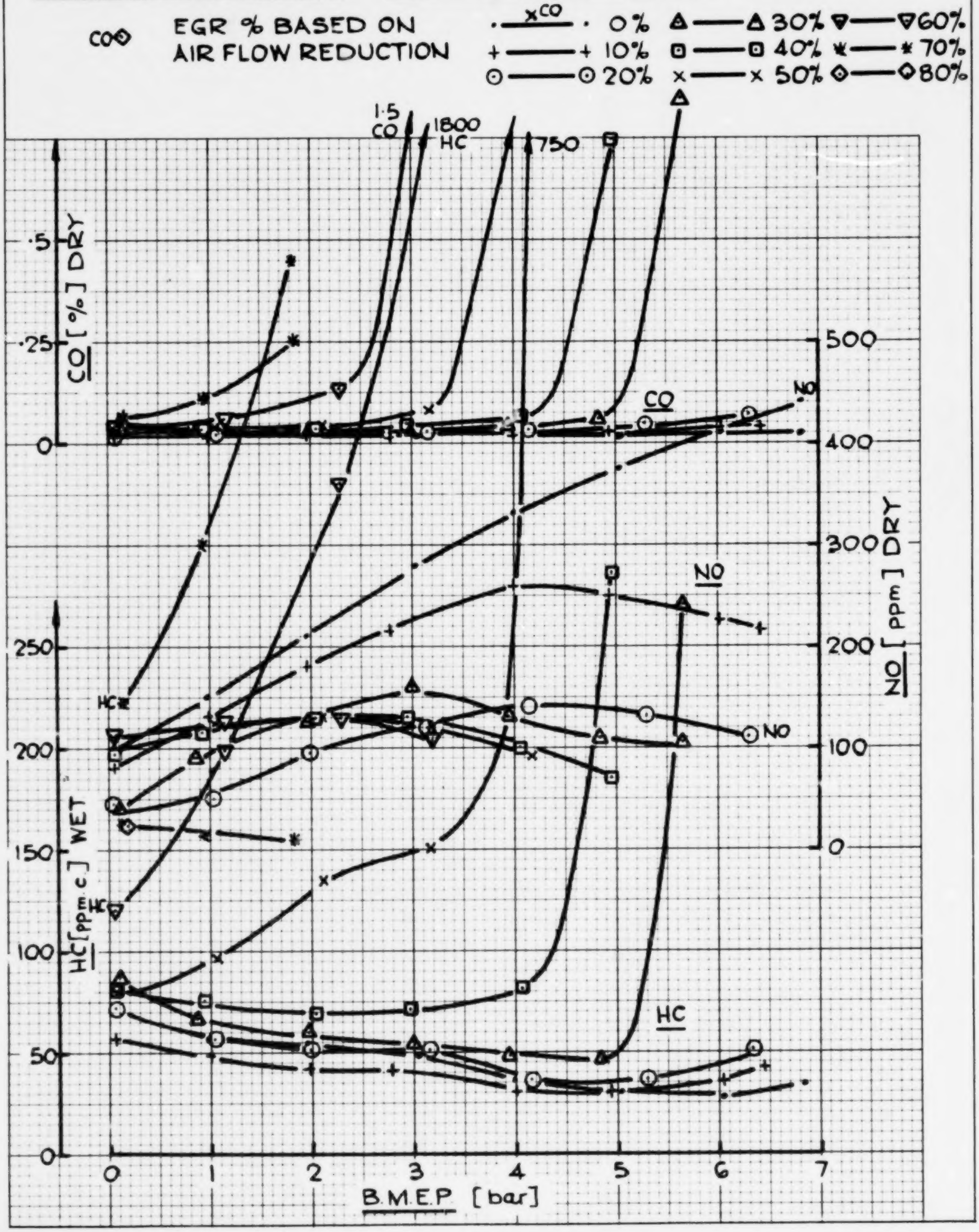
Date OCT/NOV '77

Engine Curve 78

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.

CURVES SHOWING EFFECT OF EGR ON HC, CO & NO EMISSIONS AT 25 rev/s - TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

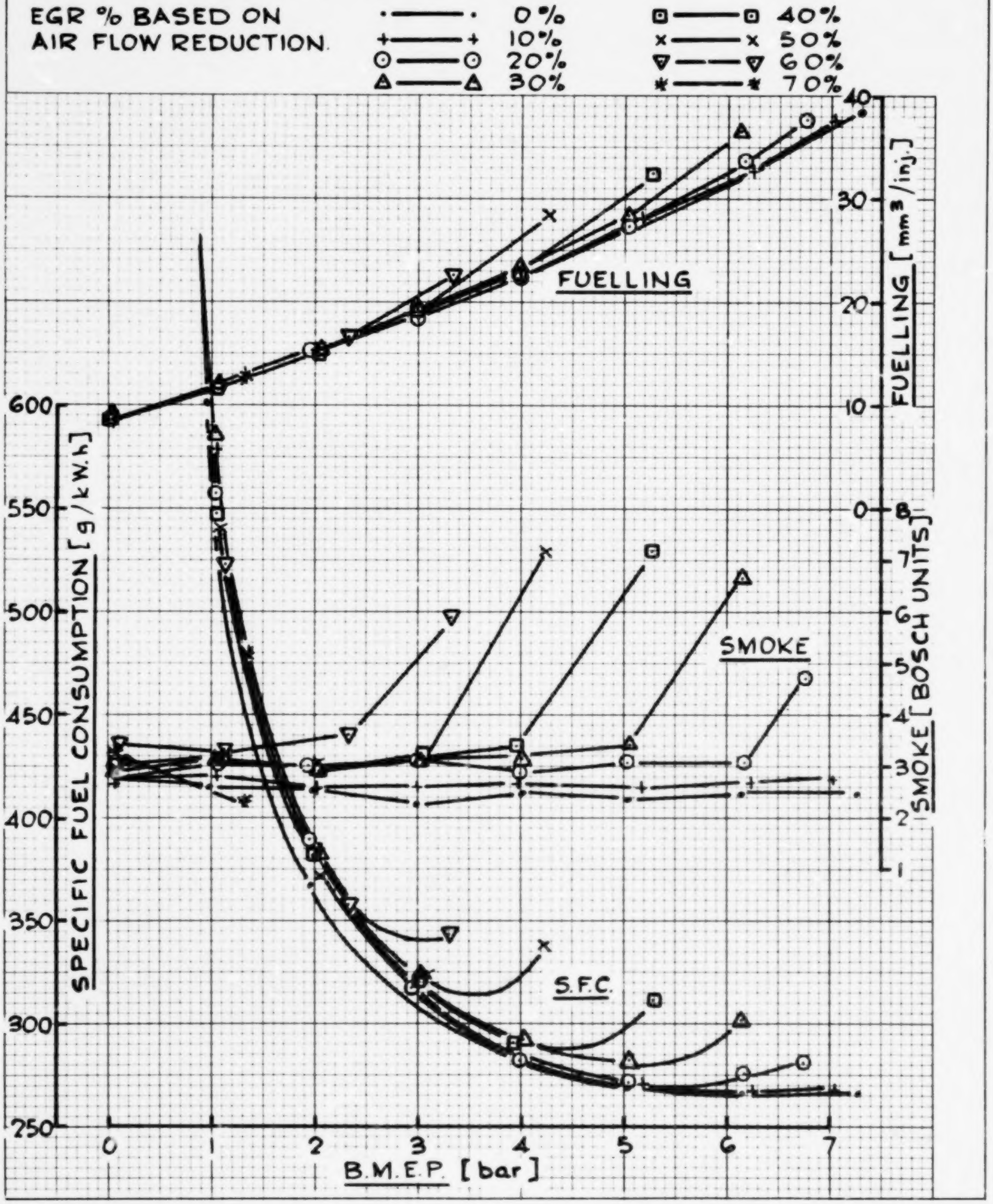
FIG. No. 98
Drg. No. D34989
Date OCT/NOV '77
Engine Curve 79

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.

CURVES SHOWING EFFECT OF EGR ON ENGINE PERFORMANCE AT 35 rev/s

TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 99

Drg. No. D34990

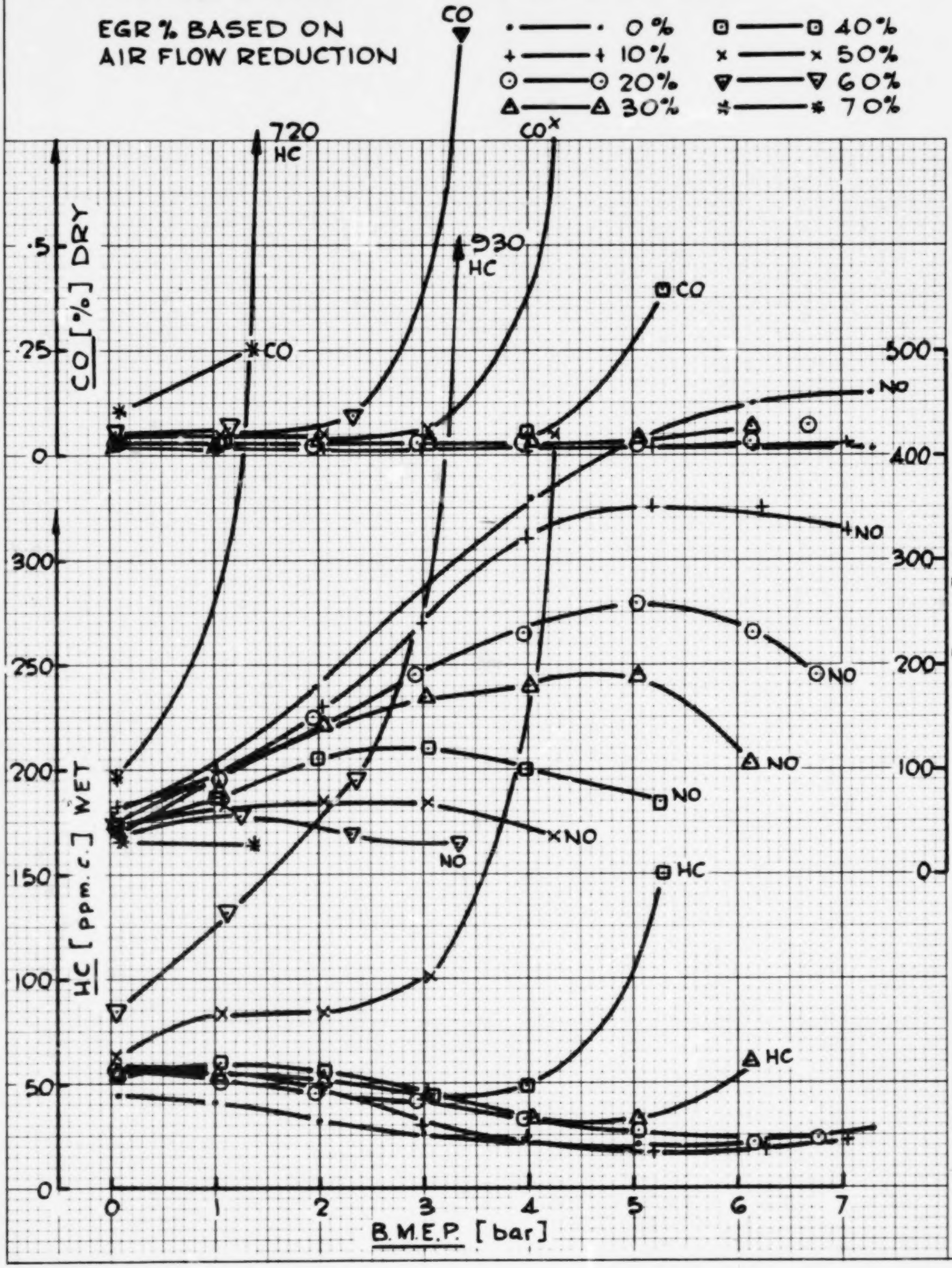
Date OCT/NOV '77

Engine Curve 80

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92.4 mm x 5 CYL.

CURVES SHOWING EFFECT OF EGR ON NO, HC & CO EMISSIONS AT 35 rev/s. - TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 100

Drg. No. D34991

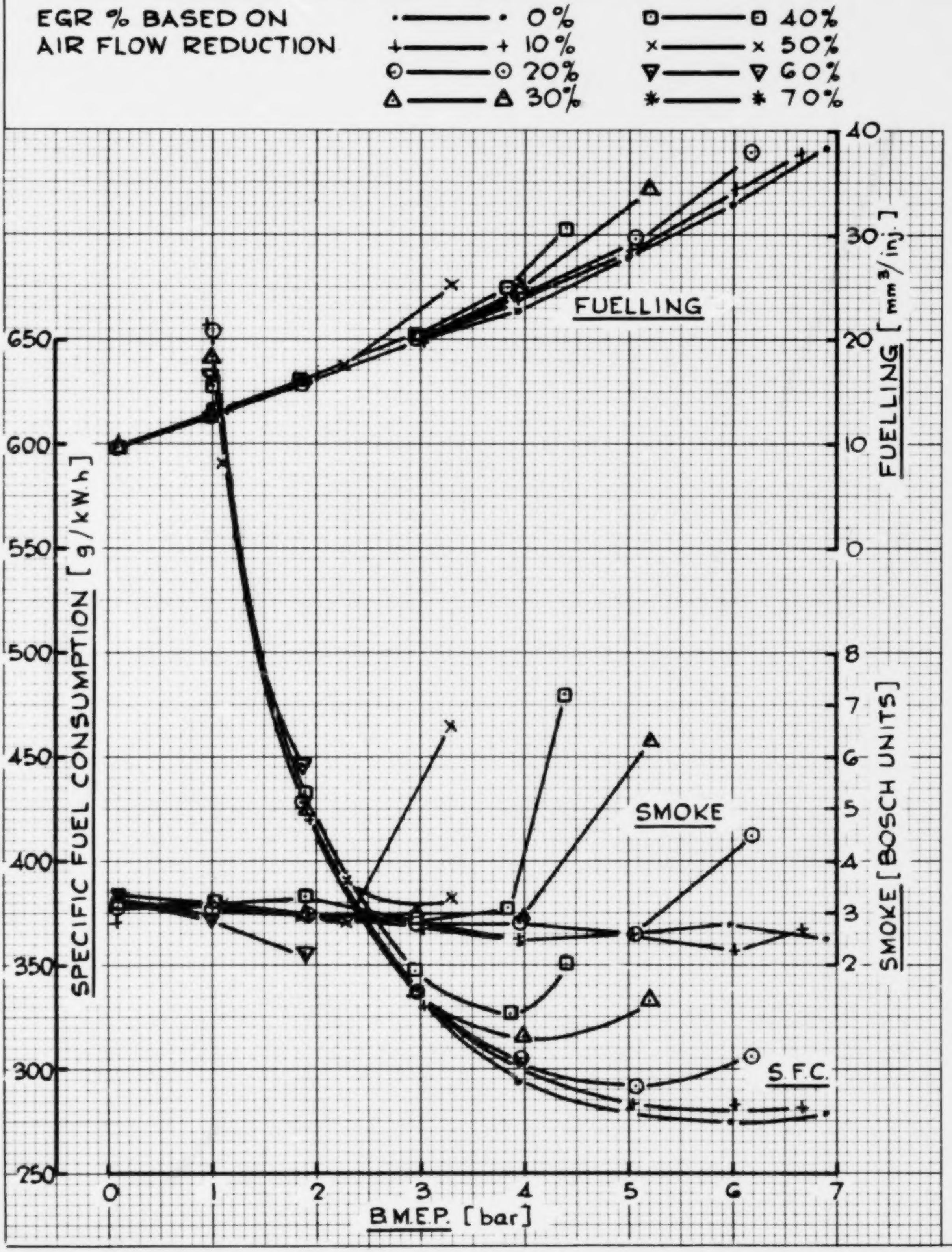
Date OCT/NOV'77

Engine Curve 81

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5 CYL.

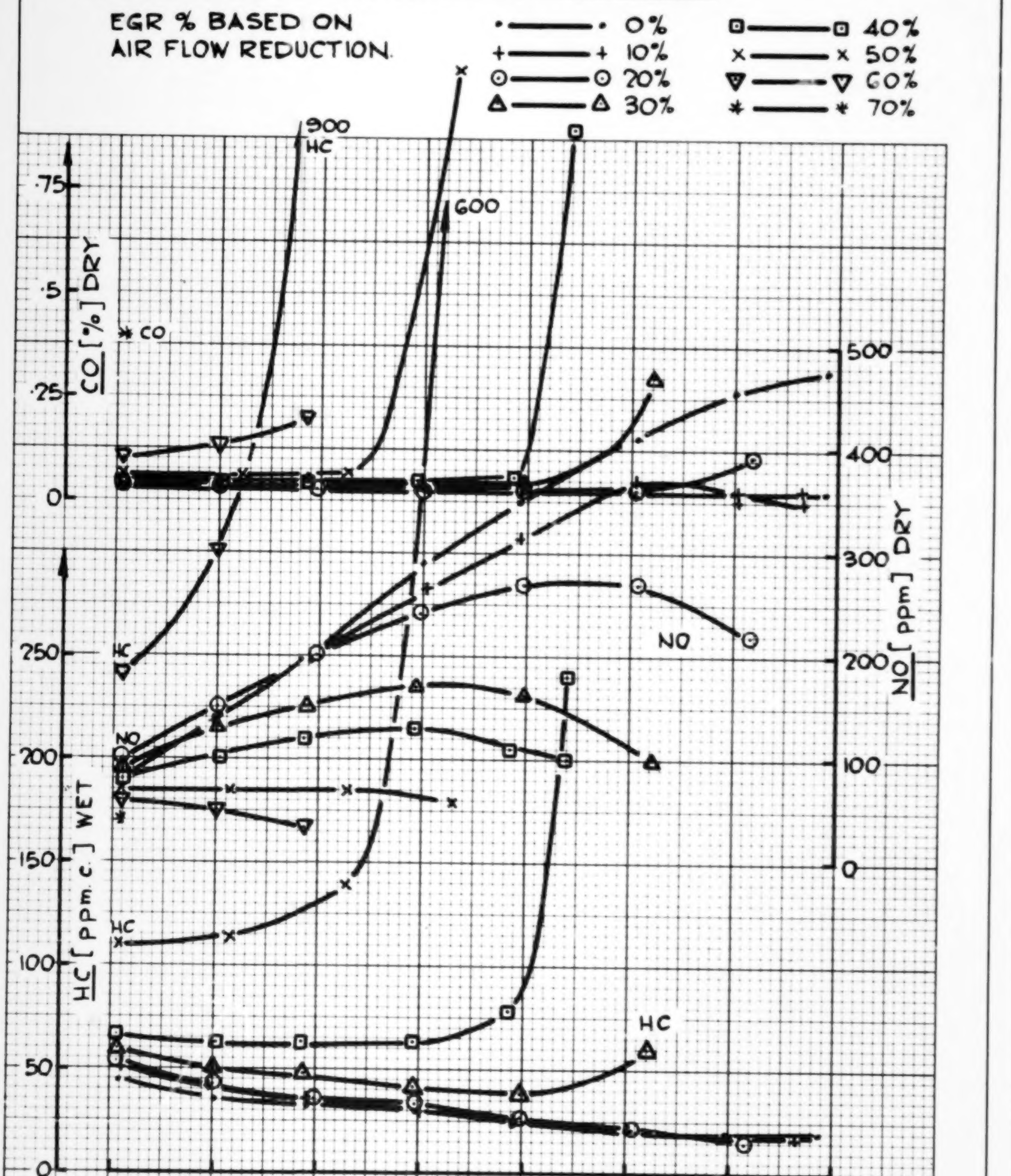
CURVES SHOWING EFFECT OF EGR ON ENGINE PERFORMANCE AT 45 rev/s. – TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 101
Drg. No. D34992
Date OCT/NOV '77
Engine Curve 82

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
CURVES SHOWING EFFECT OF EGR ON NO, CO & HC EMISSIONS AT 45 rev/s - TURBOCHARGED BUILD.



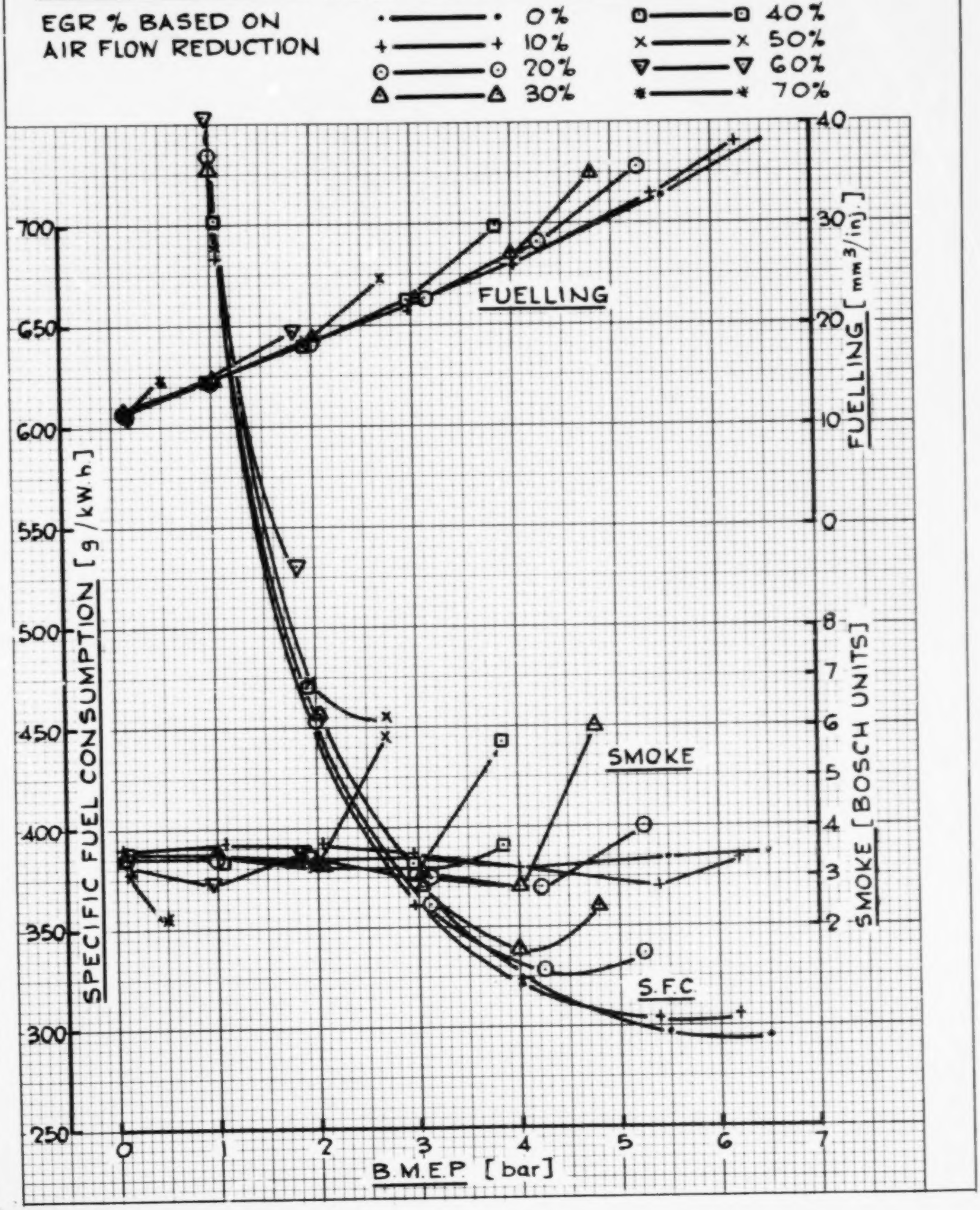
RICARDO CONSULTING ENGINEERS

FIG. No. 102
Drg. No. D34993
Date OCT/NOV77
Engine Curve 83

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5 CYL.

CURVES SHOWING EFFECT OF EGR ON ENGINE PERFORMANCE AT 55 rev/s. - TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 103

Drg. No. D34994

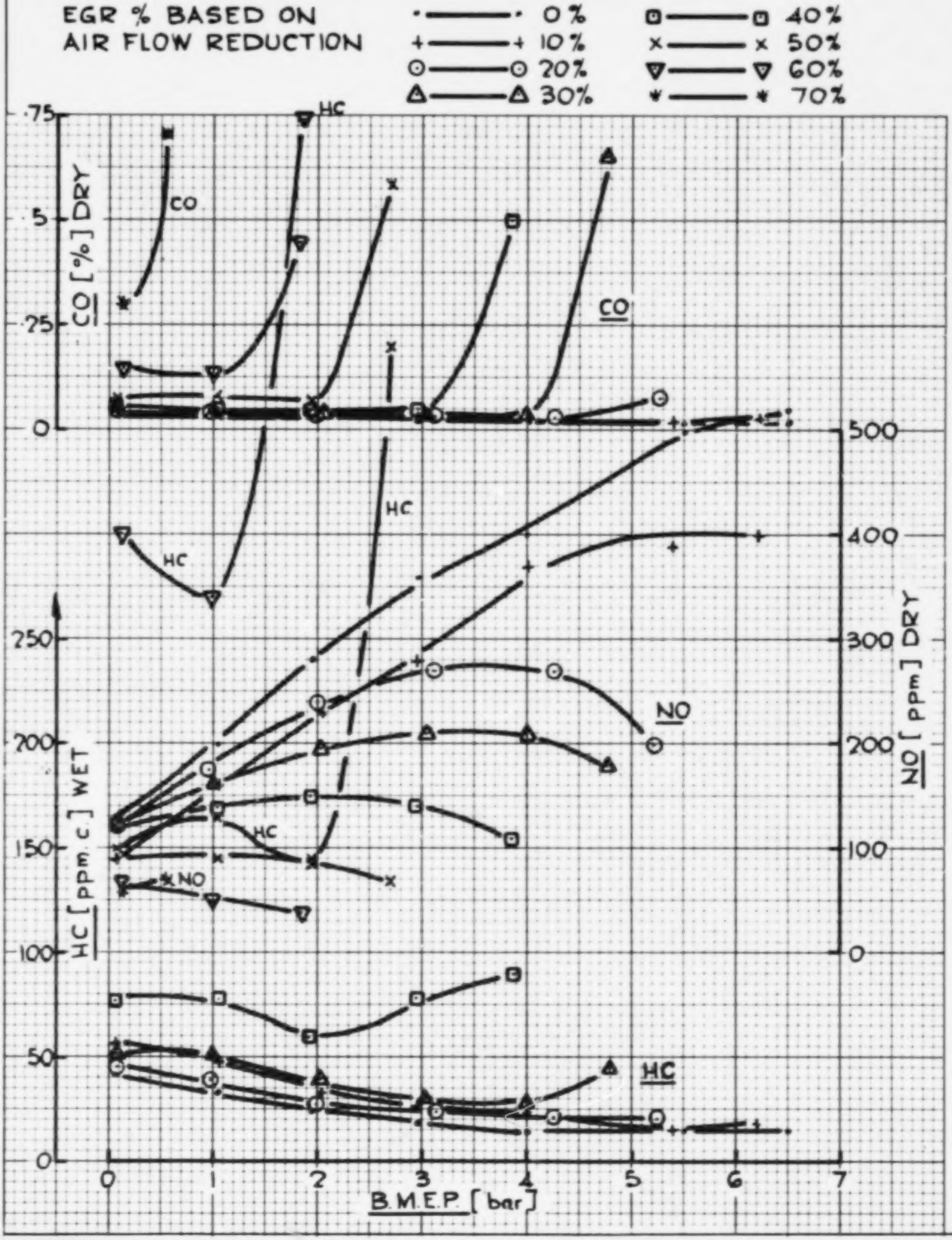
Date OCT/NOV '77

Engine Curve 84

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.

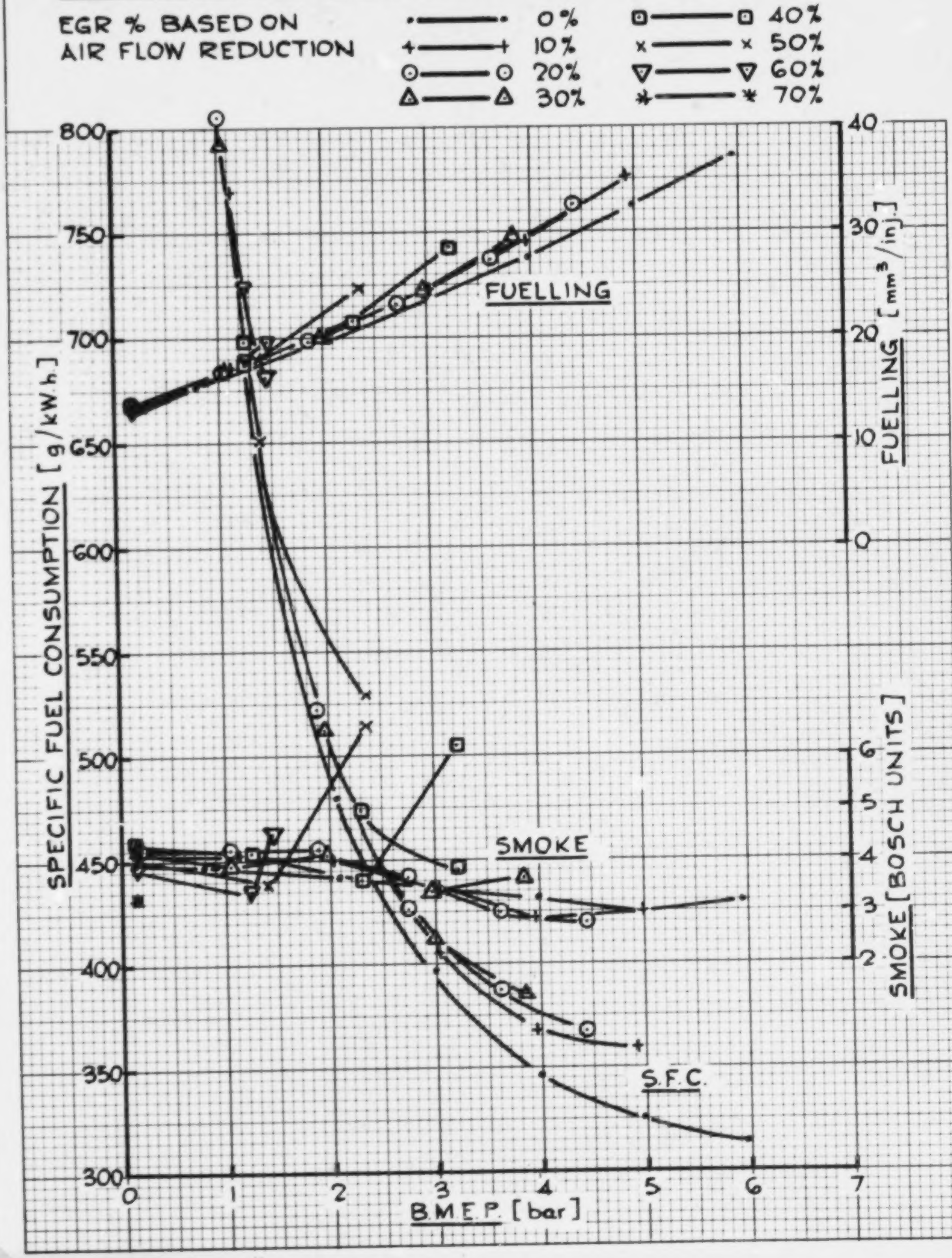
CURVES SHOWING EFFECT OF EGR ON HC, CO & NO EMISSIONS AT 55 rev/s. - TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

FIG. No. 104
Drg. No. D34995
Date OCT/NOV '77
Engine Curve 85

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm × 92·4mm × 5CYL.
CURVES SHOWING EFFECT OF EGR ON ENGINE PERFORMANCE AT 65 rev/s - TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

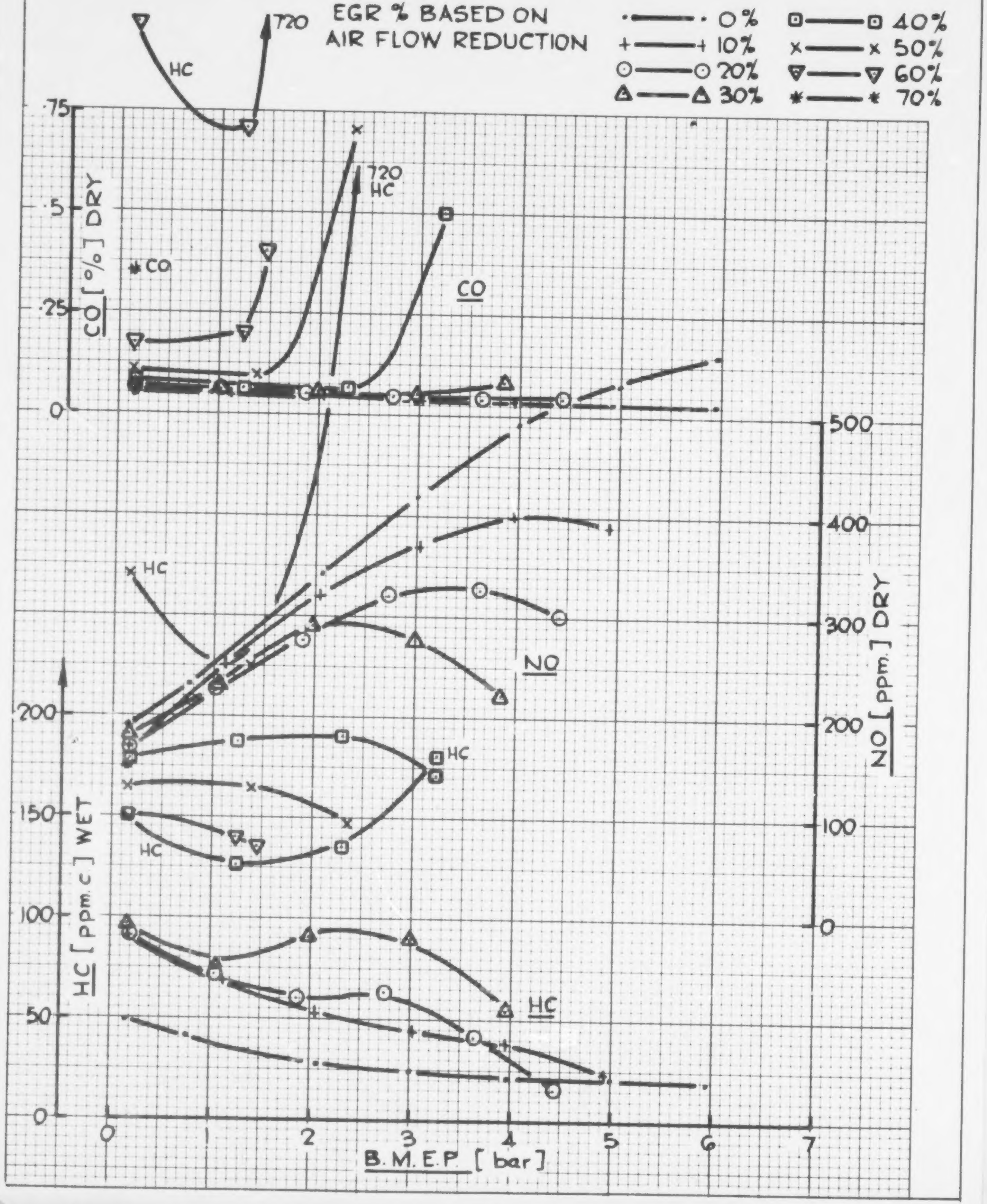
FIG. No.	105
Drg. No.	D34996
Date	OCT/NOV'77

Engine Curve 86

EPA MODULATED EGR STUDY

MERCEDES OMG17 ENGINE 91 mm X 92·4 mm X 5 CYL.

CURVES SHOWING EFFECT OF EGR ON CO, HC & NO EMISSIONS AT 65 rev/s. - TURBOCHARGED BUILD



RICARDO CONSULTING ENGINEERS

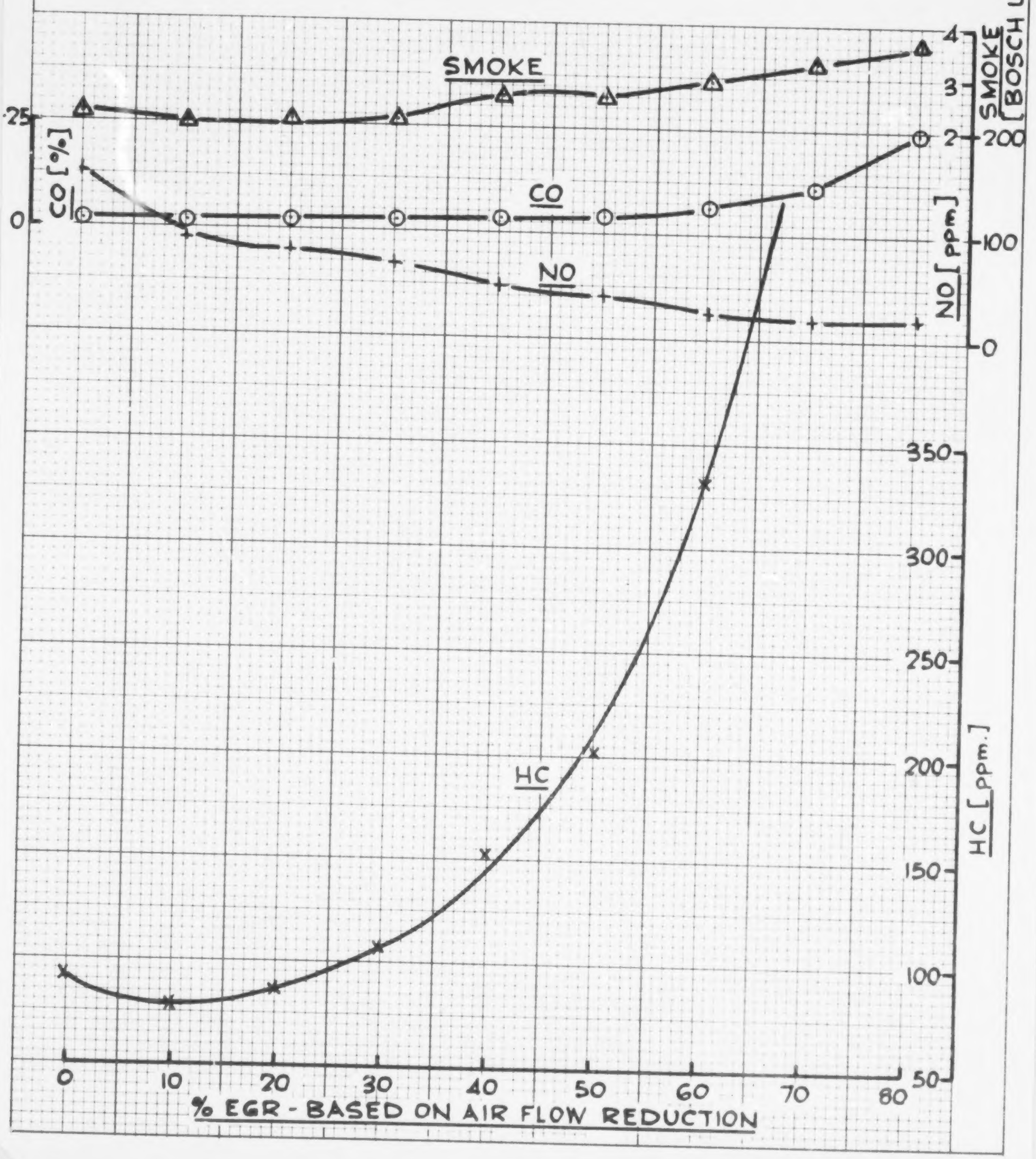
FIG. No. 106
Drg. No. D34997
Date NOV. '77
Engine Curve No. 87

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

CURVES SHOWING EFFECT OF EGR AT IDLE (10 rev/s) ON SMOKE, CO, HC & NO EMISSIONS.

TURBOCHARGED BUILD



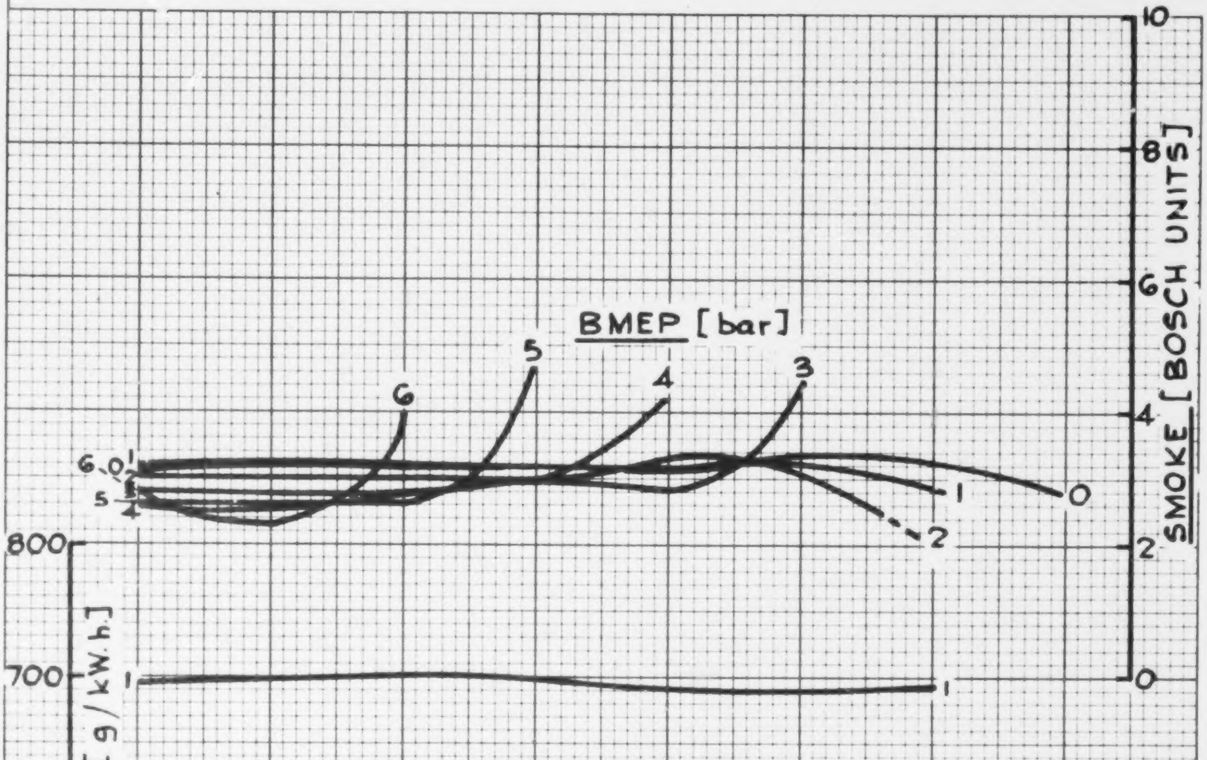
RICARDO CONSULTING ENGINEERS

FIG. No. 107
Drg. No. D34998
Date NOV. '77
Engine Curve 81A

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.

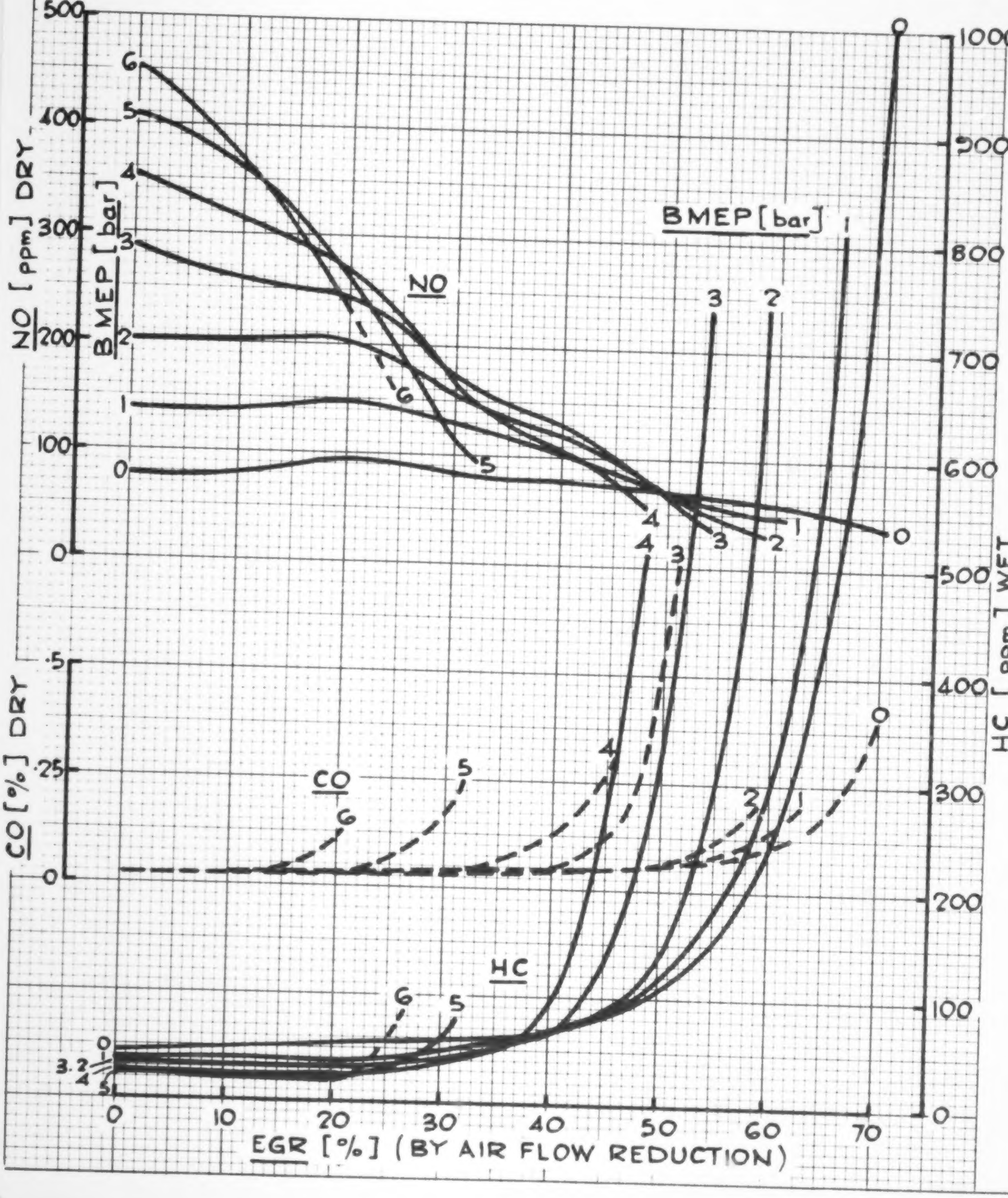
CURVES SHOWING EFFECT OF EGR ON SPECIFIC FUEL CONSUMPTION AND SMOKE AT CONSTANT LOADS-45 rev/s



RICARDO CONSULTING ENGINEERS

FIG. No. 108
Drg. No. D34999
Date NOV. '77
Engine Curve 82A

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5 CYL.
CURVES SHOWING EFFECT OF EGR ON GASEOUS EMISSIONS AT CONSTANT LOADS - 45 rev/s.



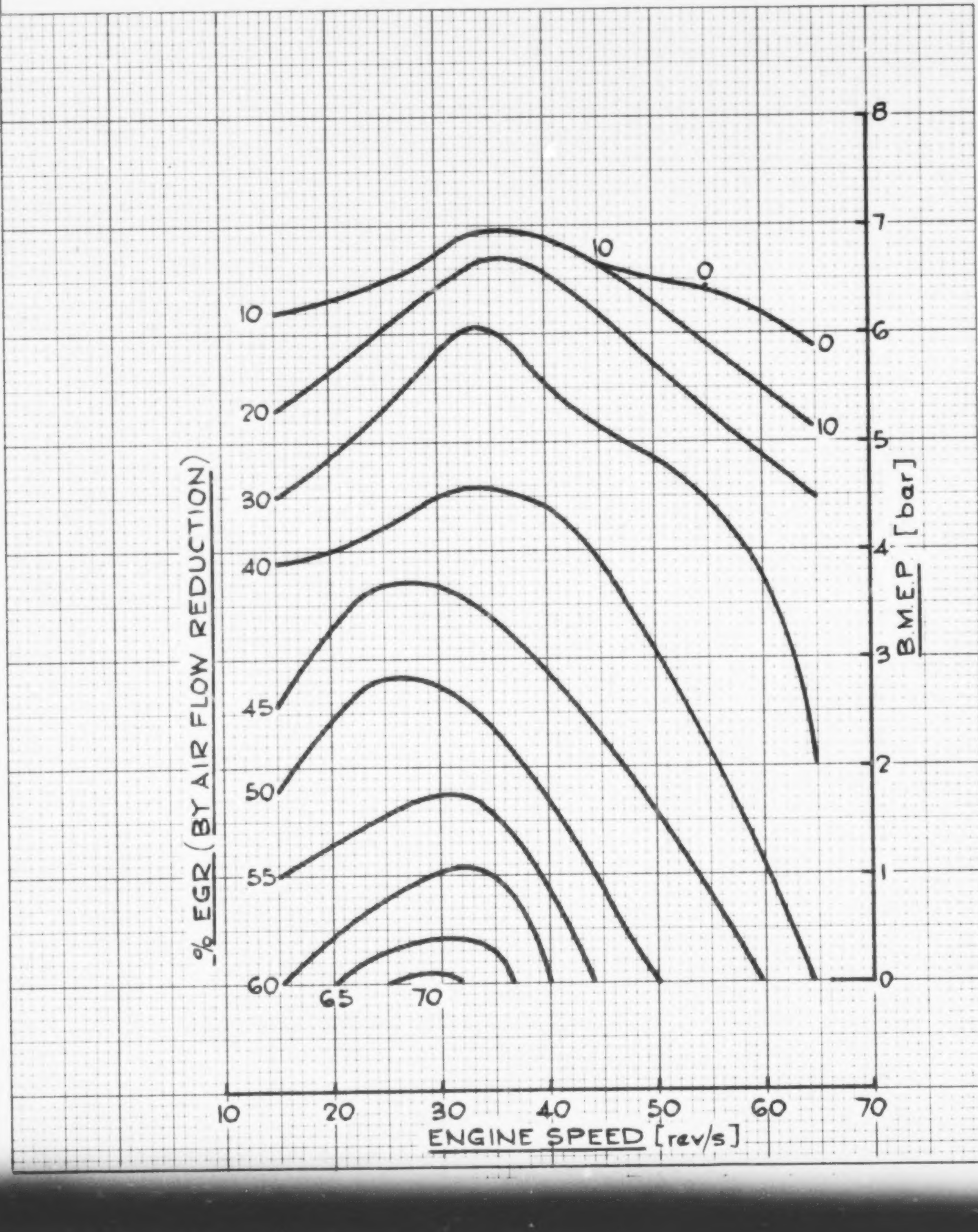
RICARDO CONSULTING ENGINEERS

FIG. No. 109
Drg. No. D35000
Date JAN. '78
Engine Curve No. 89

EPA MODULATED EGR STUDY

COMPOSITE MAP OF EGR MODULATION 1.

EGR LEVELS OBTAINED FROM MERCEDES OM 617 STEADY STATE RESULTS TO GIVE 3x HC LEVEL WITHOUT LOSS OF MAXIMUM POWER



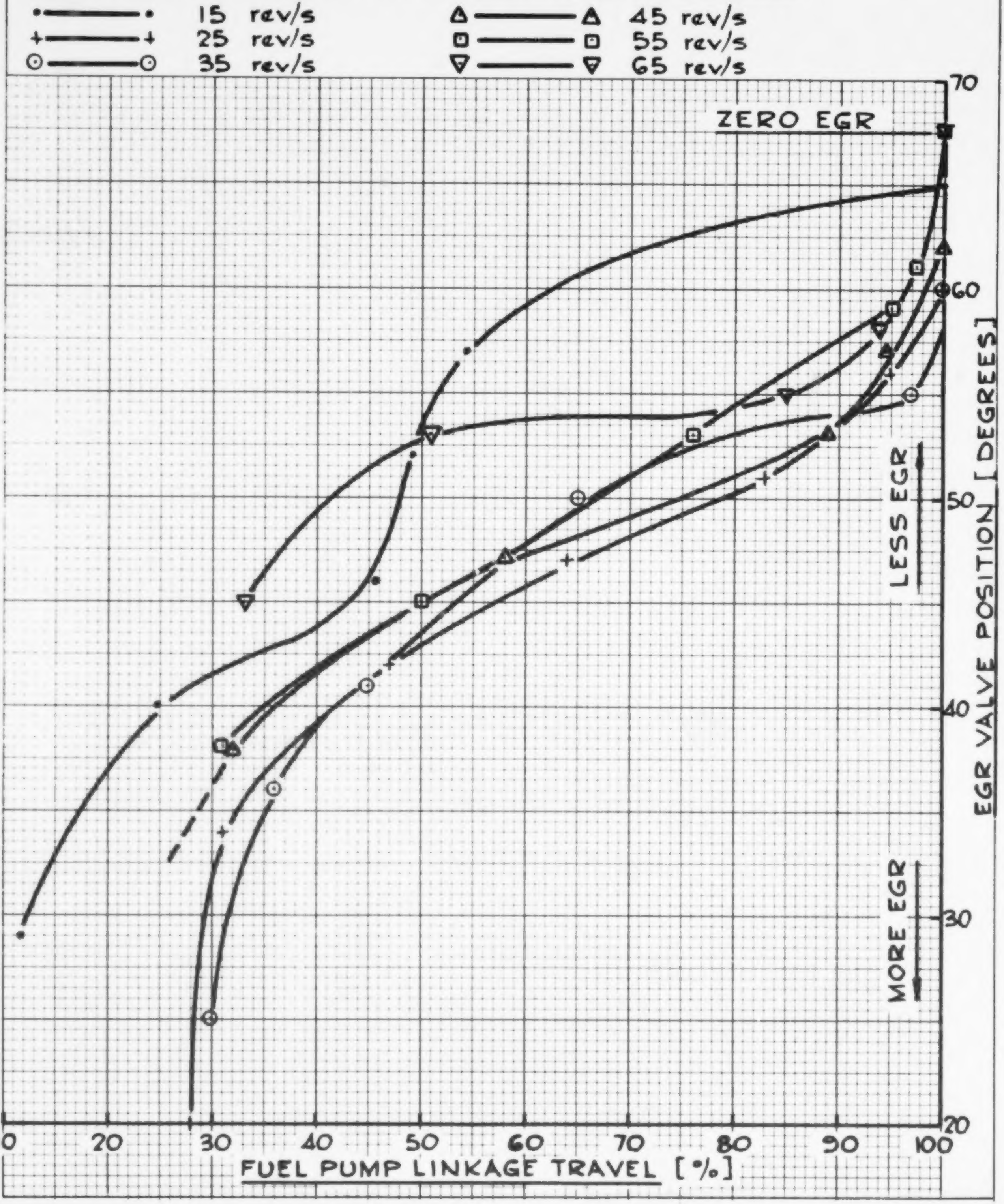
RICARDO CONSULTING ENGINEERS

FIG. No. 110
Drg. No. D35001
Date JAN '78
Engine Curve 90

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

CURVES SHOWING RELATIONSHIP BETWEEN EGR VALVE POSITION AND FUEL PUMP LINKAGE POSITION FOR EGR MODULATION 1. (BASED ON 3 x HC LEVELS)



RICARDO CONSULTING ENGINEERS

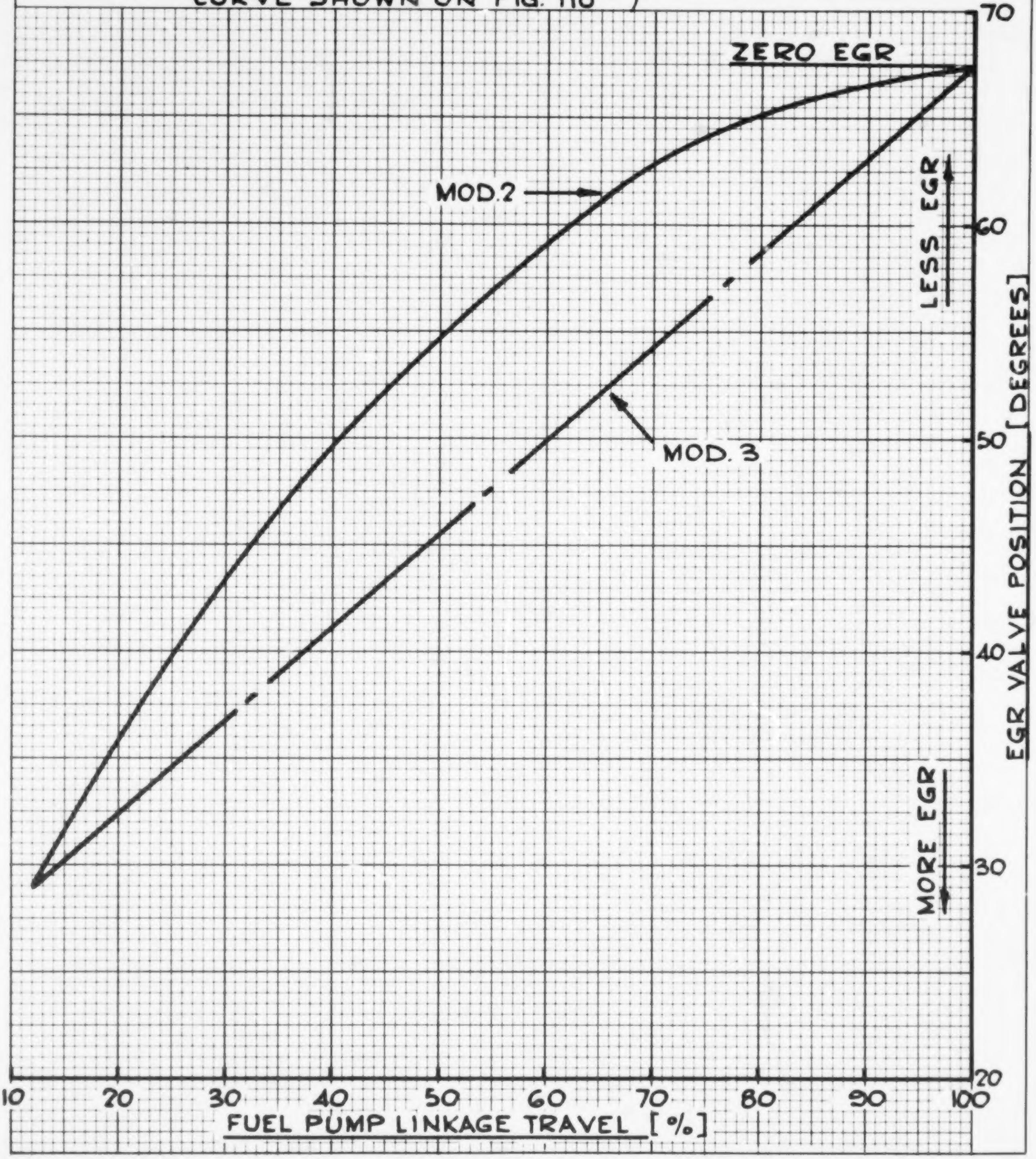
FIG. No. 111
Drg. No. D35002
Date JAN '78
Engine Curve 91

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.

CURVES SHOWING RELATIONSHIP BETWEEN EGR VALVE POSITION AND FUEL PUMP LINKAGE POSITION FOR EGR MODULATIONS 2 & 3 AT ALL SPEEDS

(MOD 2 LINE BASED ON MAX EGR ON MOD 1 CURVE SHOWN ON FIG. 110)



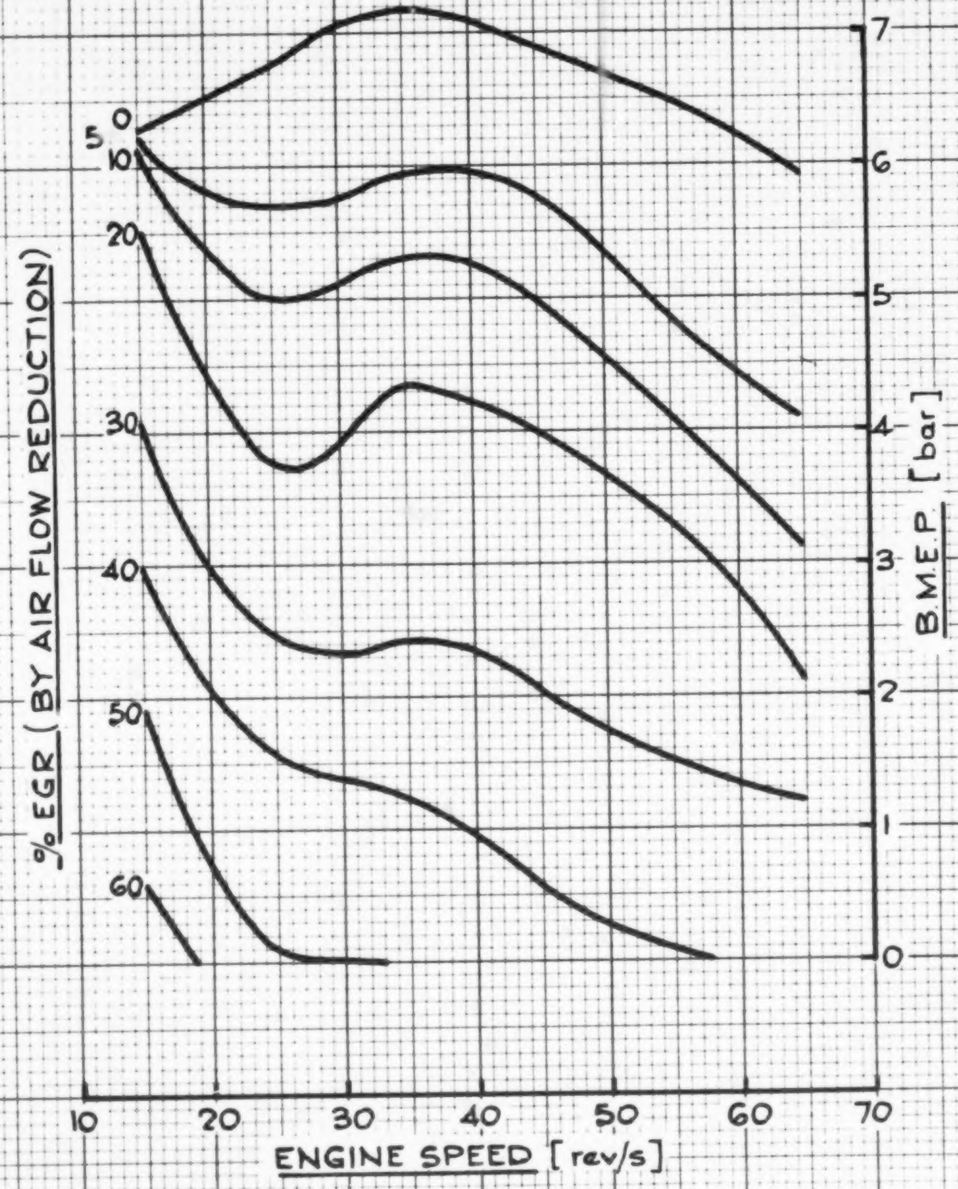
RICARDO CONSULTING ENGINEERS

FIG. No. 112
Drg. No. D35003
Date JAN.'78
Engine Curve No. 93

EPA MODULATED EGR STUDY

COMPOSITE MAP OF EGR MODULATION 2

EGR LEVELS OBTAINED FROM DIRECT RELATIONSHIP WITH LOAD AS SHOWN IN FIG. 111



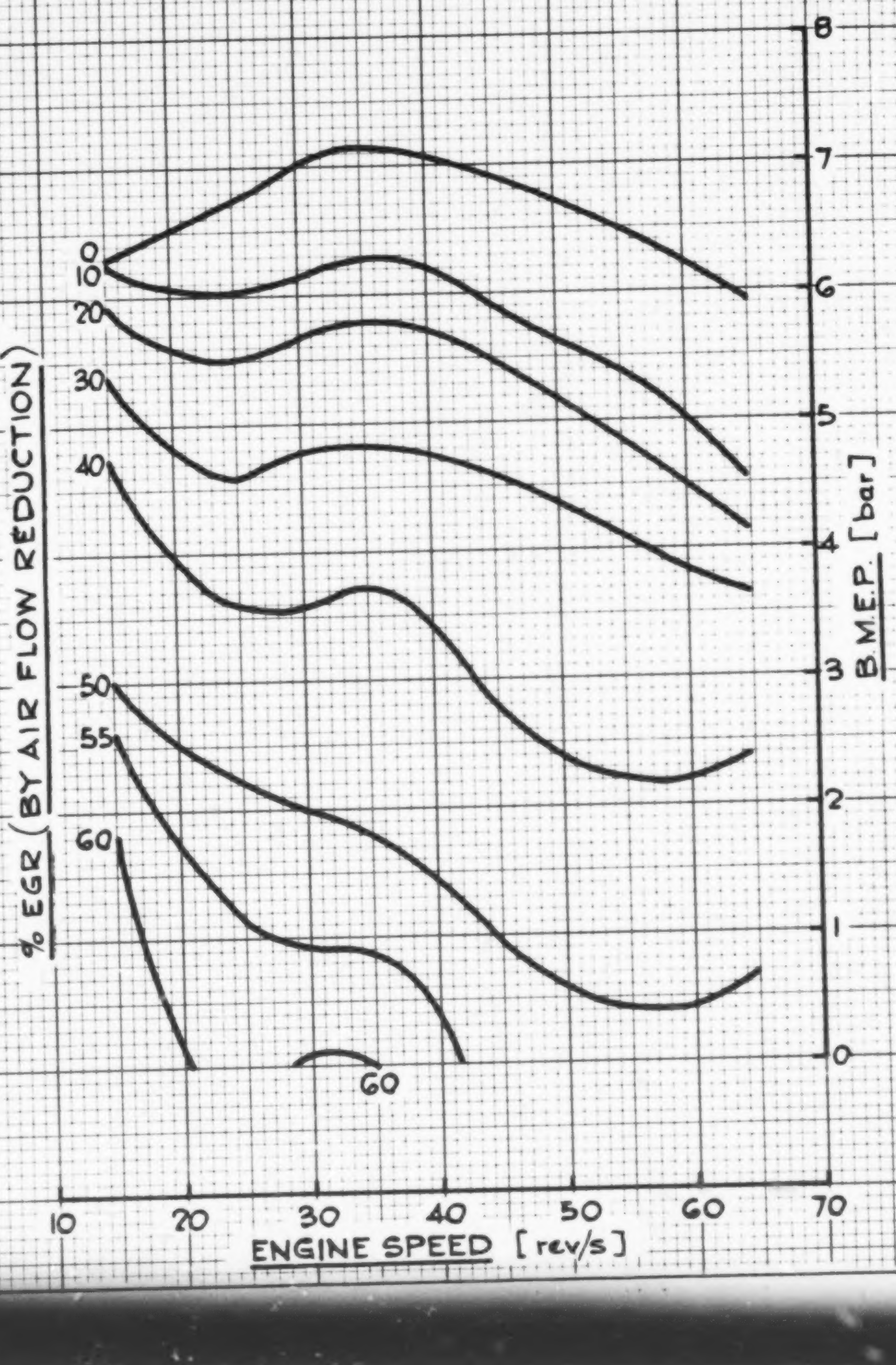
RICARDO CONSULTING ENGINEERS

FIG. No. 113
Drg. No. D35004
Date JAN. '78
Engine Curve No. 94

EPA MODULATED EGR STUDY

COMPOSITE MAP OF EGR MODULATION 3

EGR LEVELS OBTAINED FROM DIRECT RELATIONSHIP WITH LOAD AS SHOWN IN FIG. 111

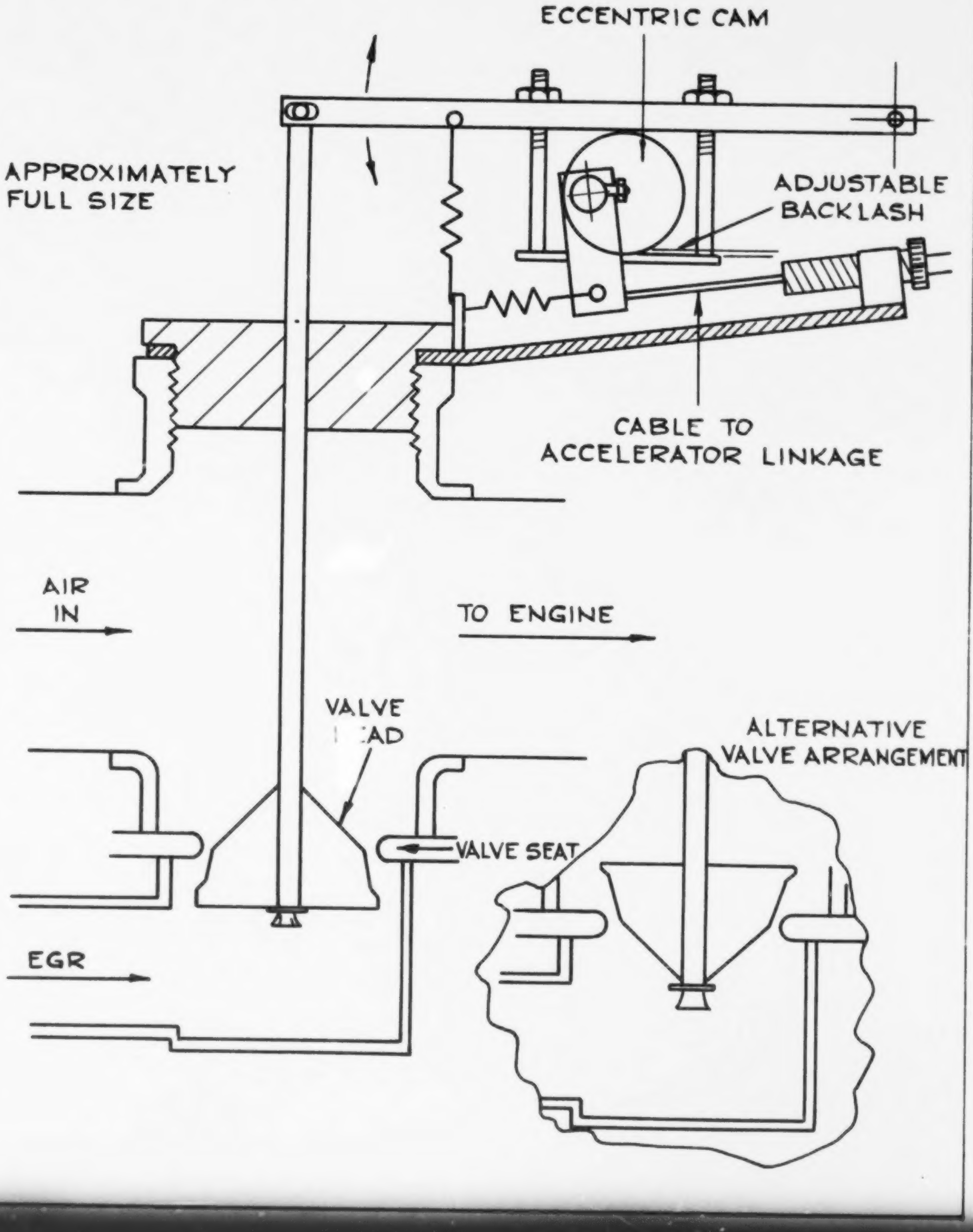


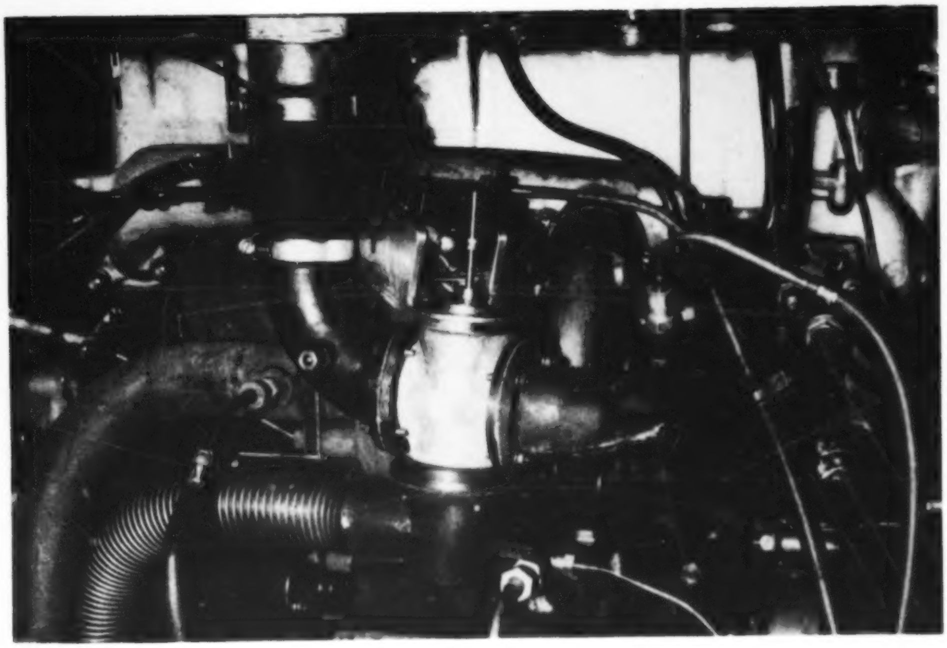
RICARDO CONSULTING ENGINEERS

FIG. No. 114
DRG. No. D35005
DATE :- JAN.'78

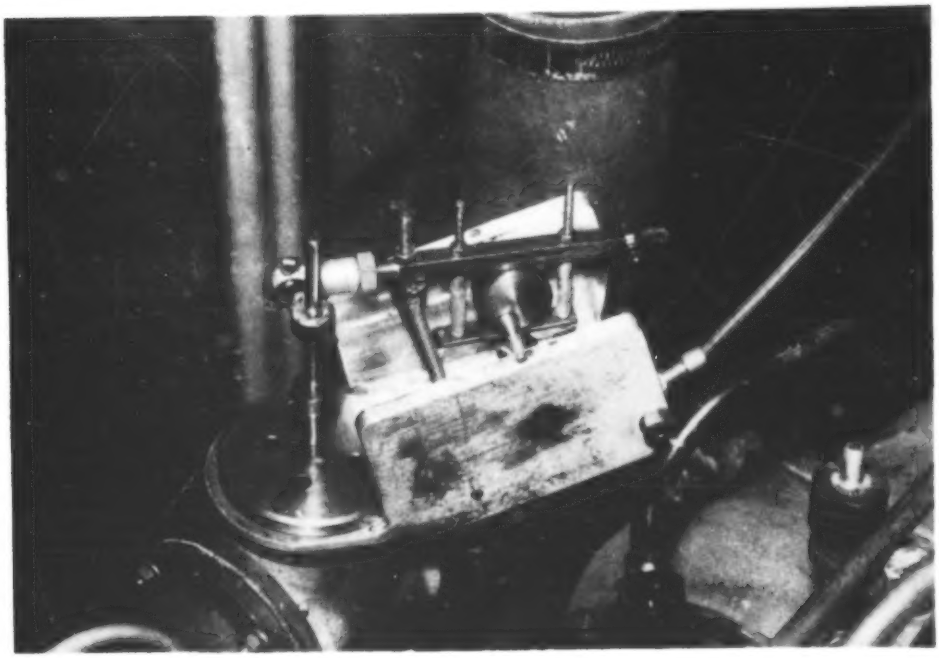
EPA MODULATED EGR STUDY

DIAGRAMMATIC SKETCH OF MK. II EGR VALVE.


ECCENTRIC CAM
APPROXIMATELY FULL SIZE
ADJUSTABLE BACKLASH
CABLE TO ACCELERATOR LINKAGE
AIR IN
TO ENGINE
VALVE HEAD
ALTERNATIVE VALVE ARRANGEMENT
VALVE SEAT
EGR



a. Mk II EGR Valve Installation



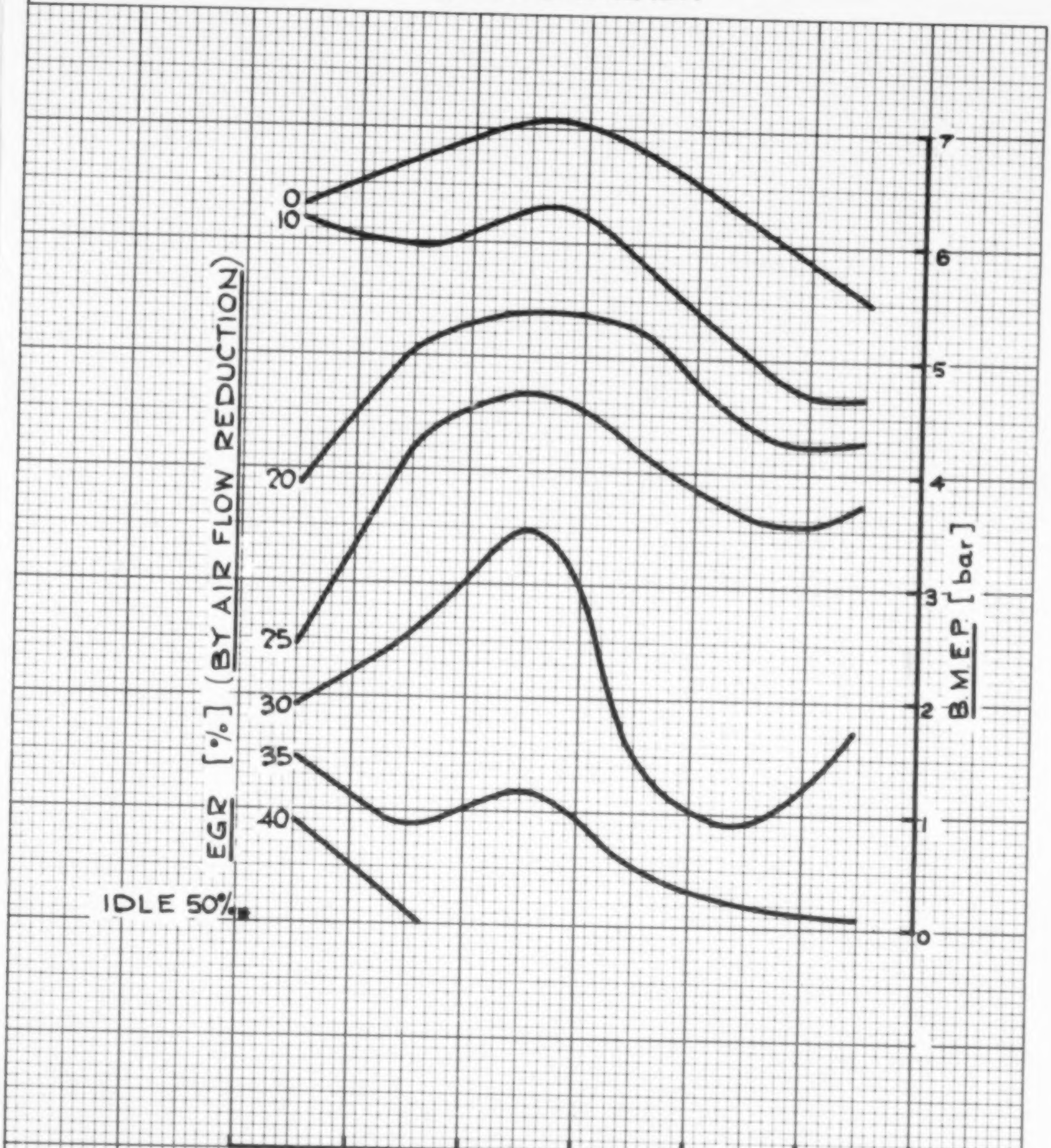
b. Installation of Valve Actuator

RICARDO CONSULTING ENGINEERS

FIG. No. 116
Drg. No. D35006
Date JAN. '78
Engine Curve No. 103

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP SHOWING EGR MODULATION A
MK. II EGR VALVE   N° 2 HEAD   N° 1 SEAT   UPWARD CLOSING
STATIC SETTINGS : 20mm LIFT AT ZERO RACK
0 mm LIFT AT 100% RACK
ZERO BACKLASH



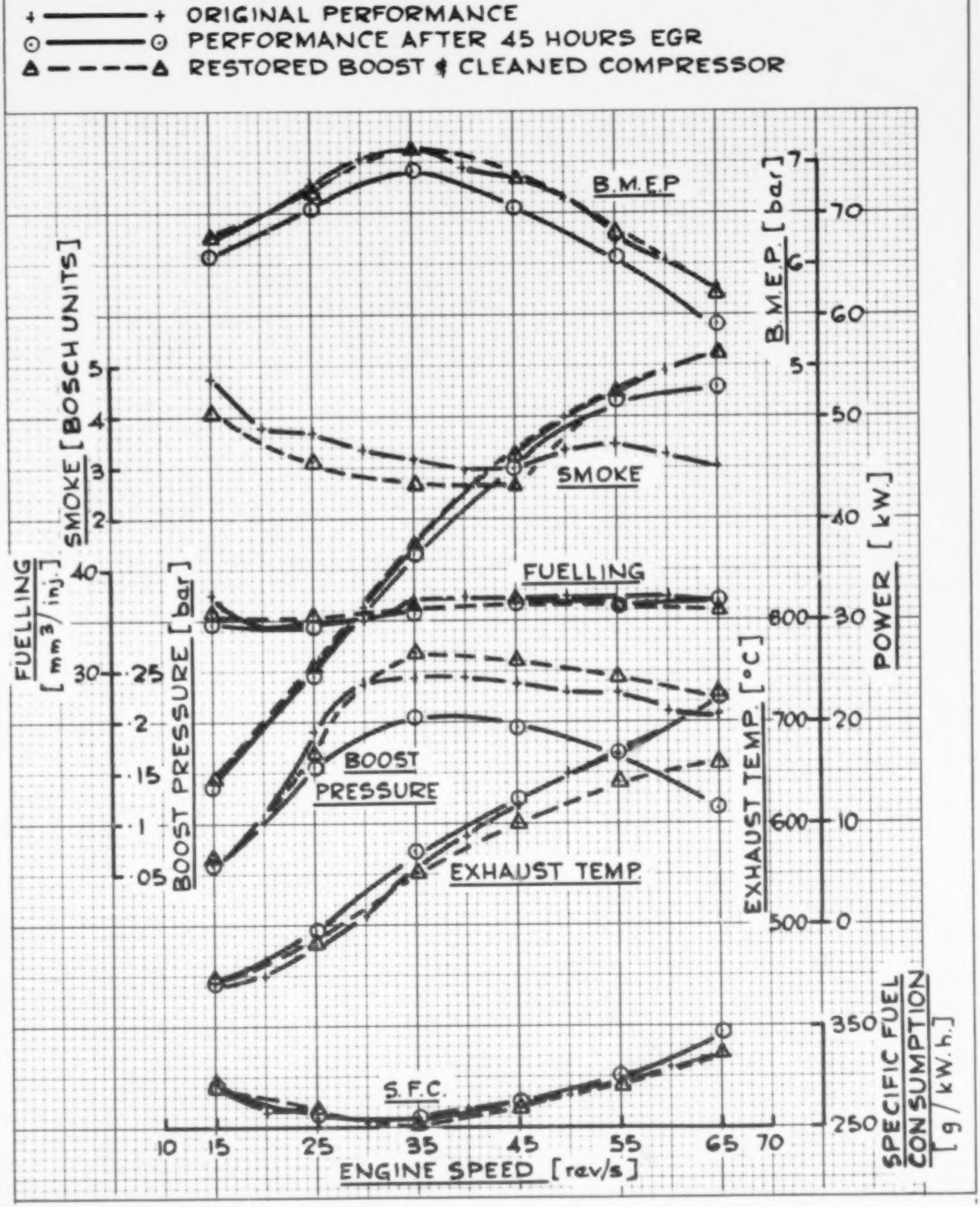
RICARDO CONSULTING ENGINEERS

FIG. No. 117
Drg. No. D35007
Date DEC'77
Engine Curve 88

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.

FULL LOAD POWER CURVES - TURBOCHARGER FITTED

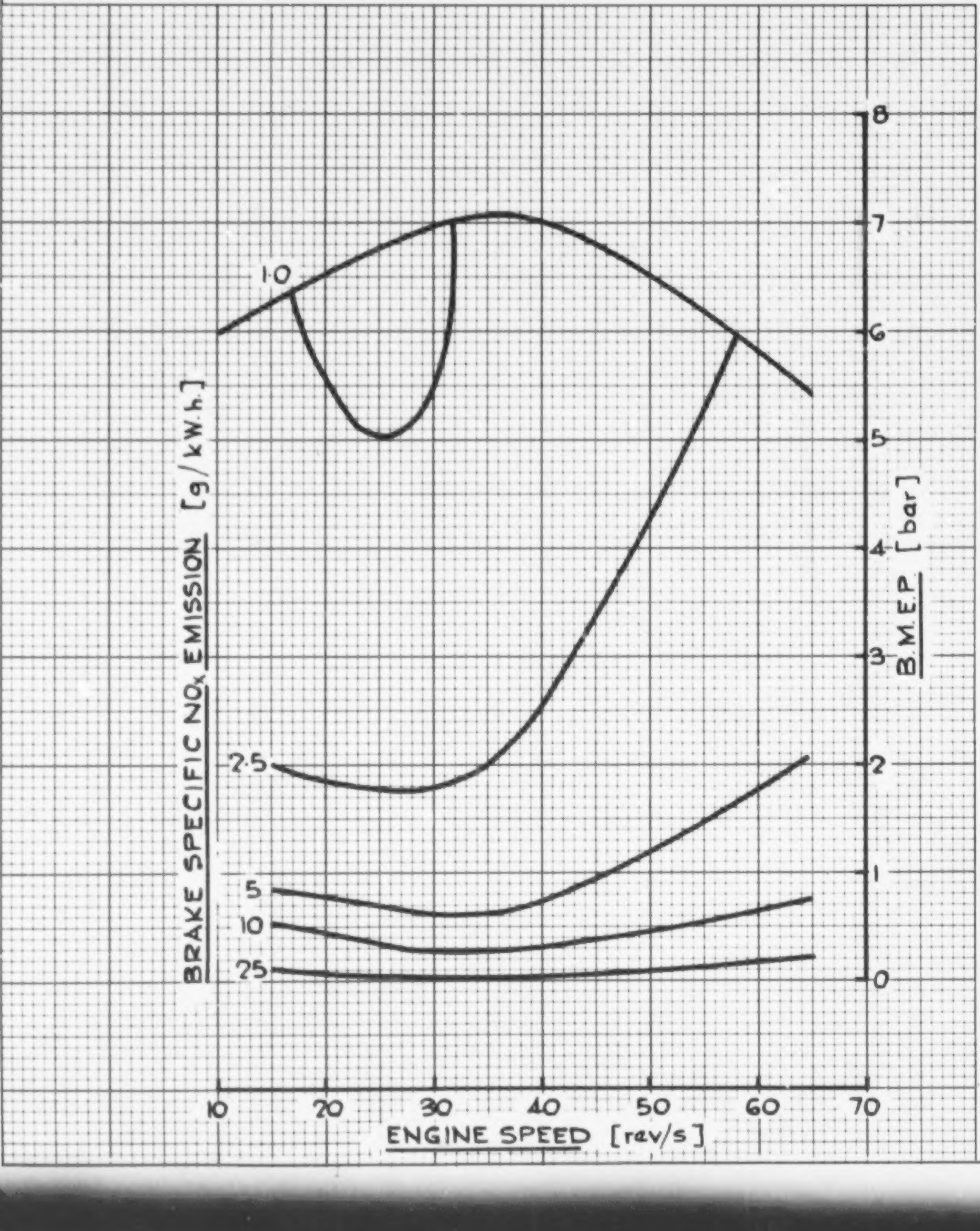


RICARDO CONSULTING ENGINEERS

FIG. No. 118
Drg. No. D35008
Date JAN. '78
Engine Curve No. 110

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC NO_x EMISSION
BASED ON EGR MODULATION A



RICARDO CONSULTING ENGINEERS

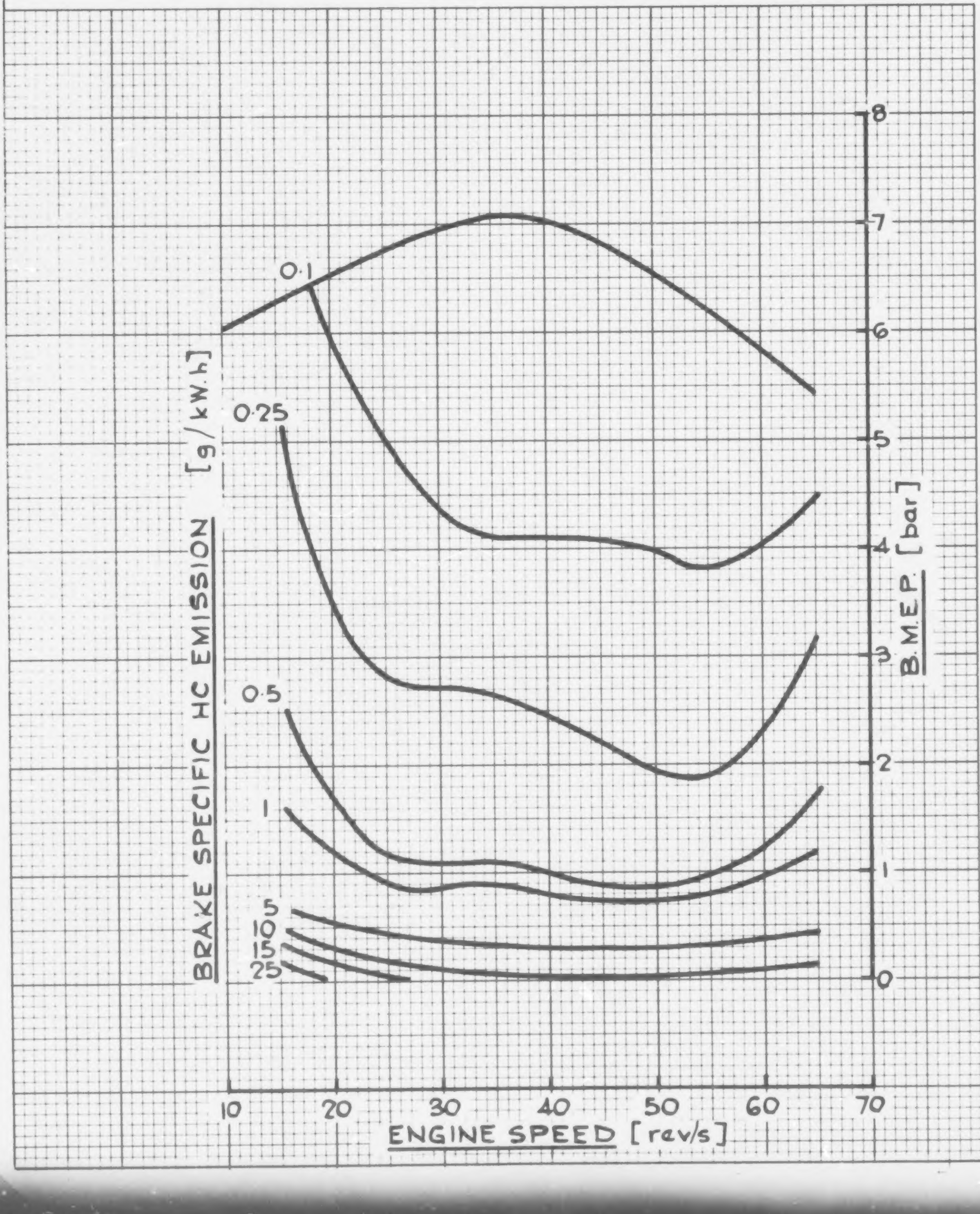
FIG. No. 119
Drg. No. D35009
Date JAN. '78
Engine Curve No 111

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC HC EMISSION
BASED ON EGR MODULATION A

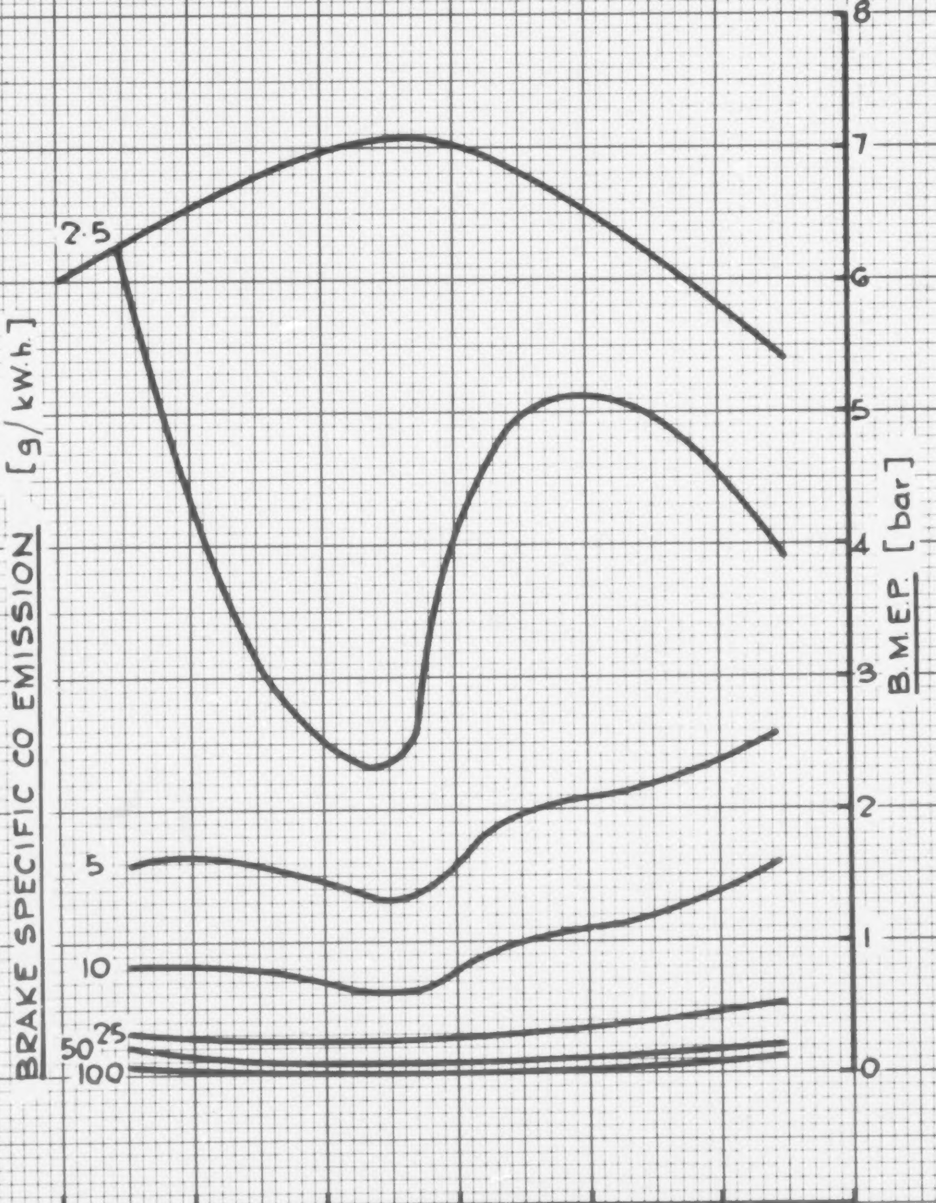


RICARDO CONSULTING ENGINEERS

FIG. No. 120
Drg. No. D35010
Date JAN '78
Engine Curve No. 112

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC CO EMISSION BASED ON EGR MODULATION A

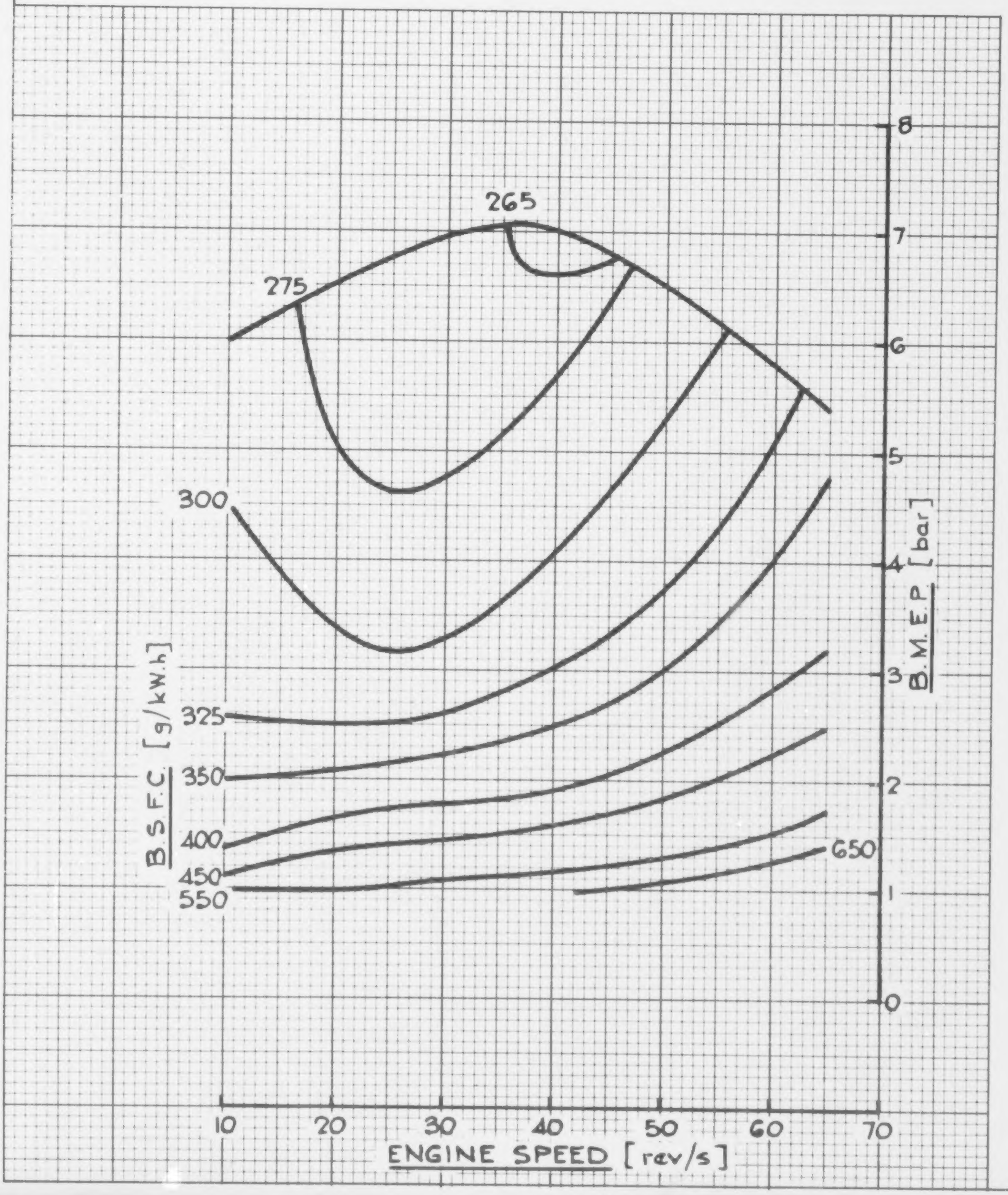


RICARDO CONSULTING ENGINEERS

FIG. No. 121
Drg. No. D35011
Date JAN. '78
Engine Curve No. 114

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC FUEL CONSUMPTION
BASED ON EGR MODULATION A

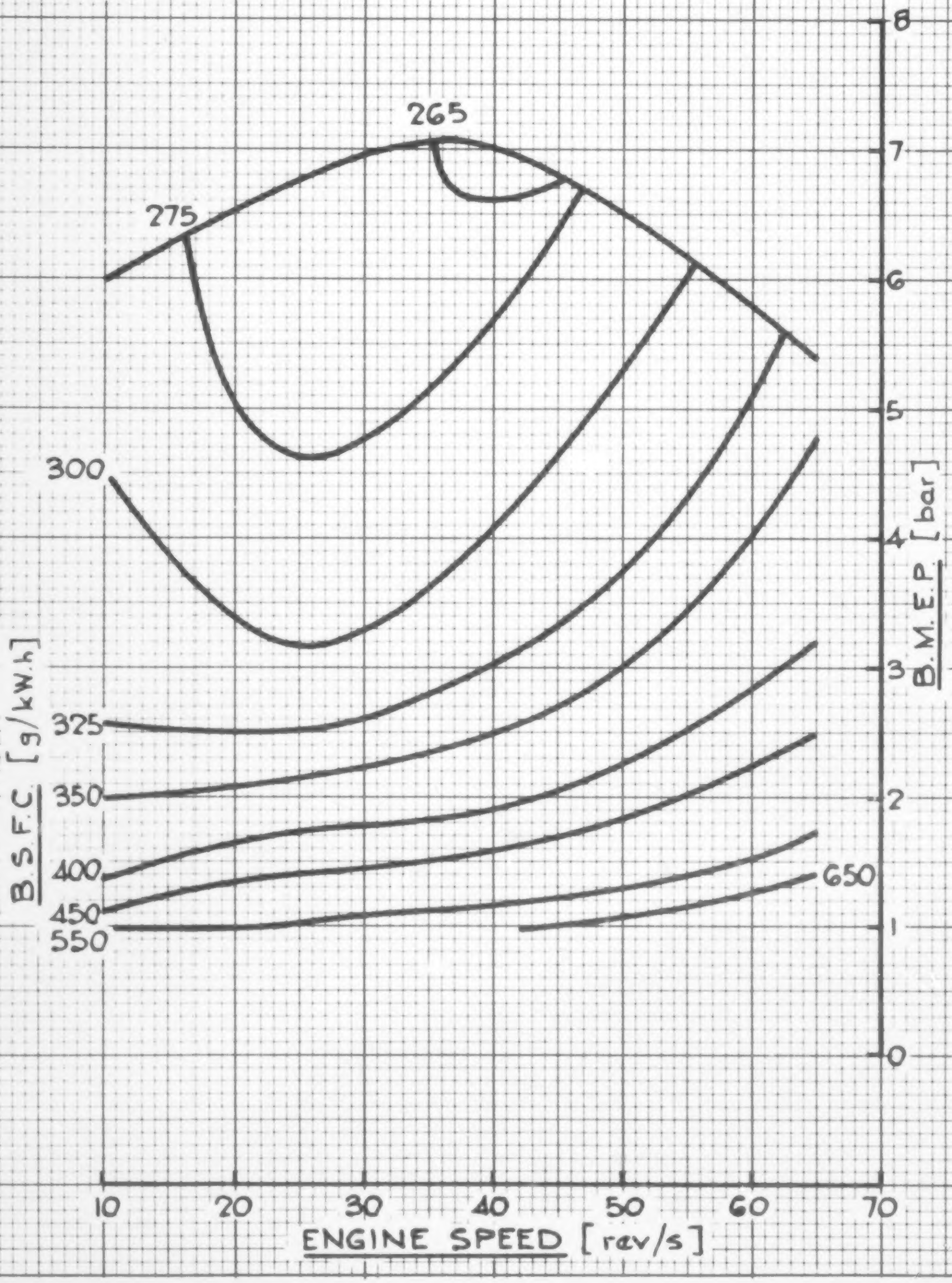


RICARDO CONSULTING ENGINEERS

FIG. No. 121
Drg. No. D35011
Date JAN. '78
Engine Curve No. 114

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92.4 mm x 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC FUEL CONSUMPTION
BASED ON EGR MODULATION A

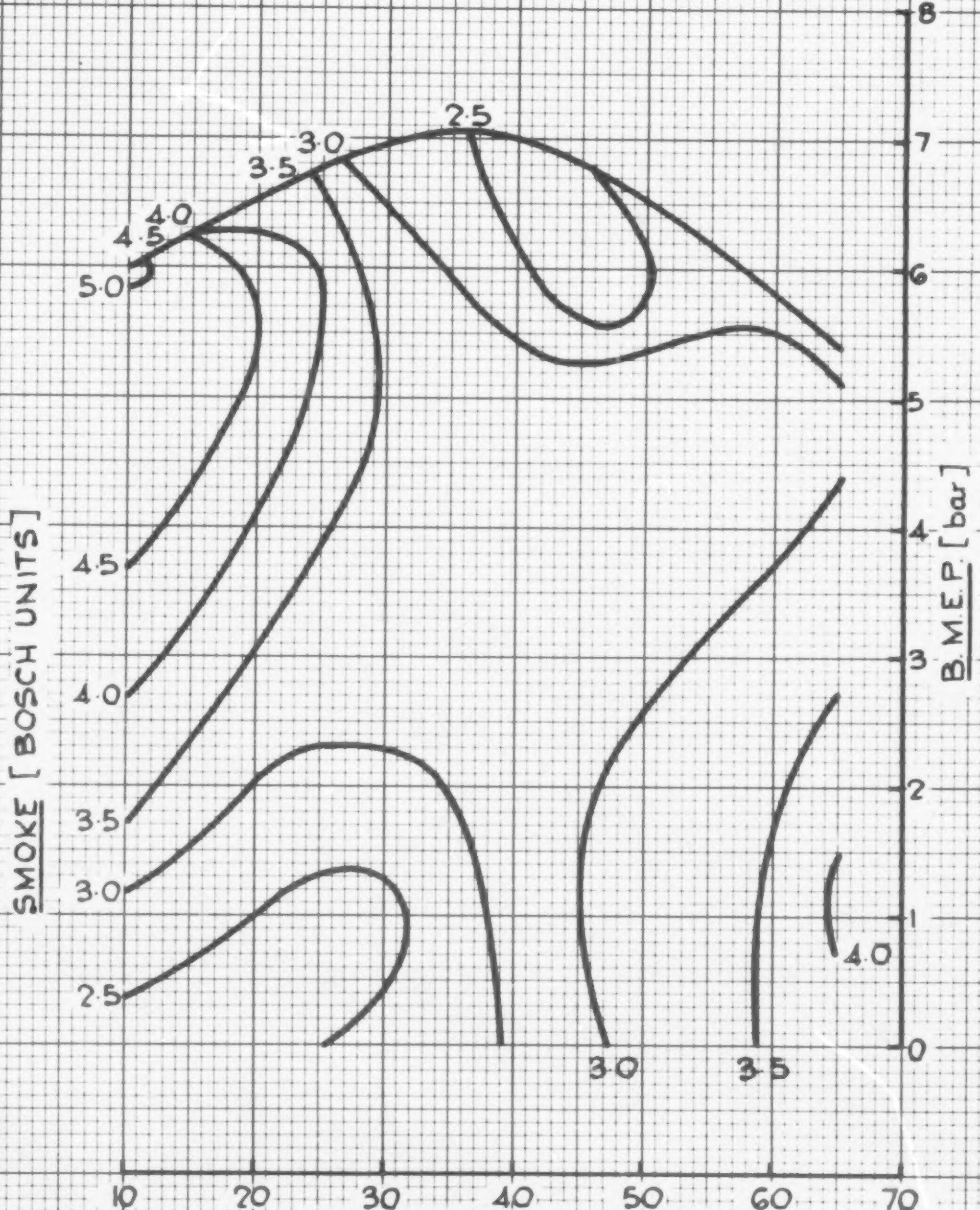


RICARDO CONSULTING ENGINEERS

FIG. No. 122
Drg. No. D35012
Date JAN. '78
Engine Curve No. 116

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF EXHAUST SMOKE DENSITY
BASED ON EGR MODULATION A



RICARDO CONSULTING ENGINEERS

FIG. No. 123
Drg. No. D35013
Date FEB. '78
Engine Curve No. 119

EPA MODULATED EGR STUDY

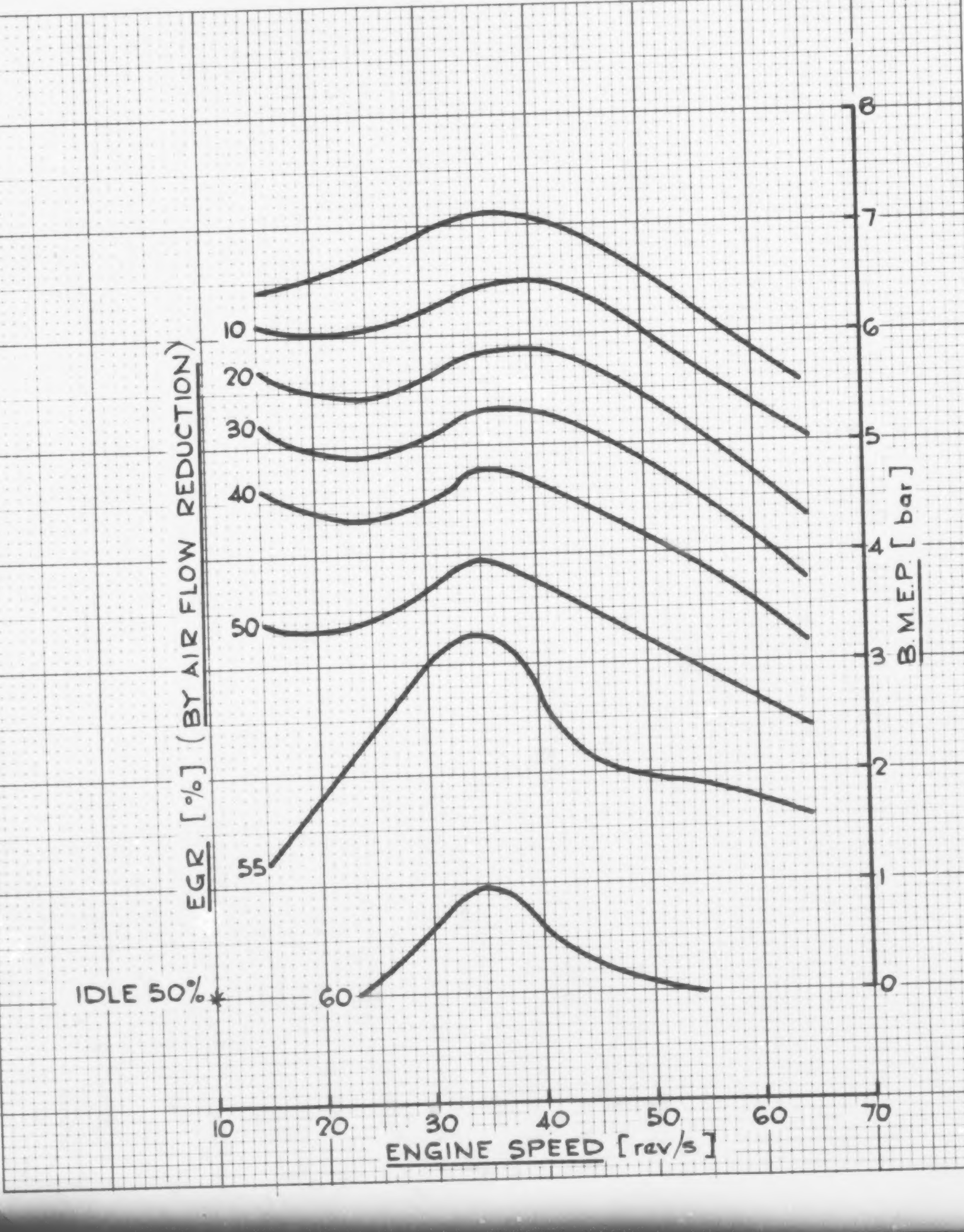
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP SHOWING EGR MODULATION B

MK. II EGR VALVE N° 3 HEAD N° 2 SEAT DOWNWARD CLOSING

STATIC SETTINGS: 44 mm LIFT AT ZERO RACK
0 mm LIFT AT 100% RACK
ZERO BACKLASH

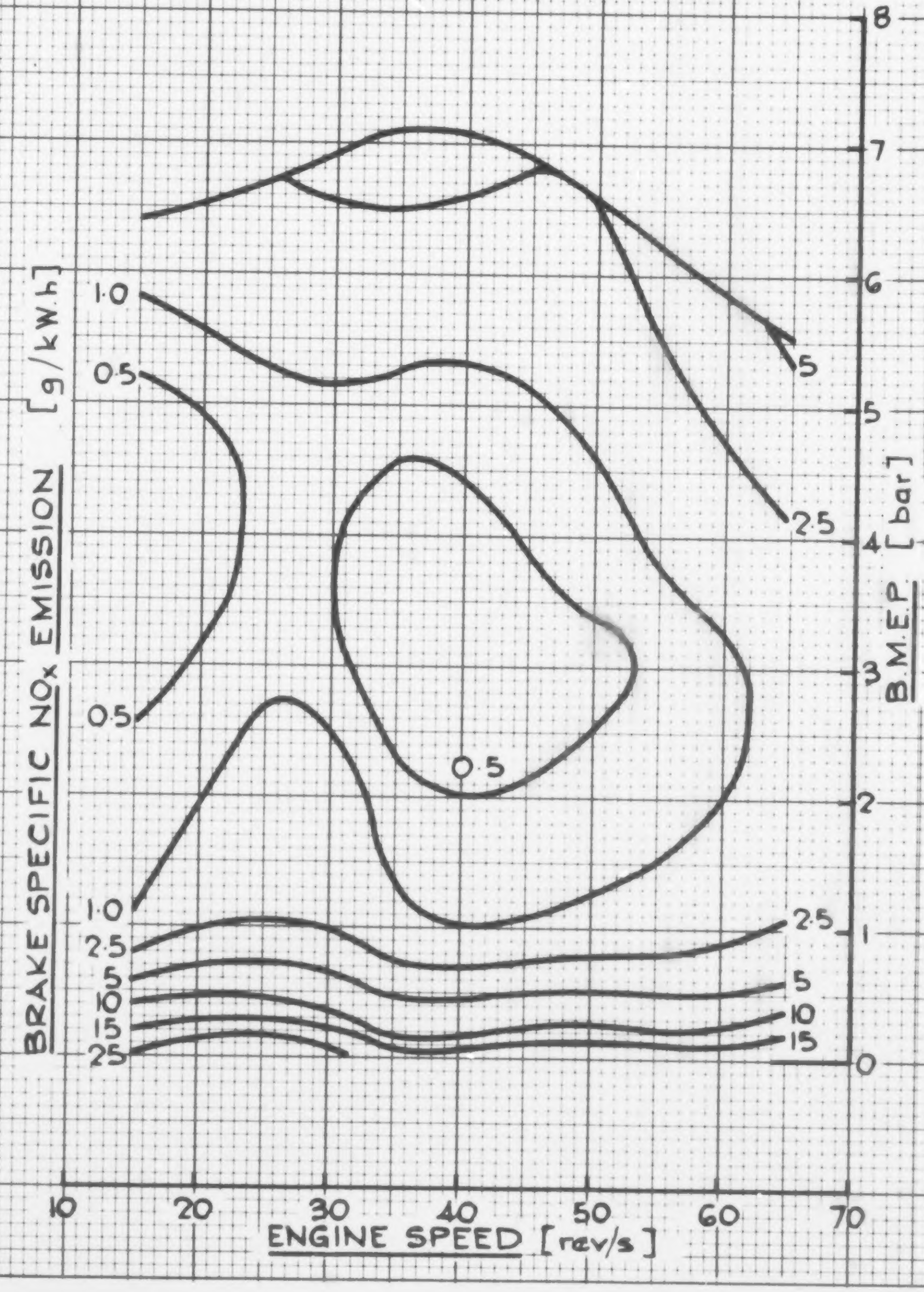


RICARDO CONSULTING ENGINEERS

FIG. No. 124
Drg. No. D35014
Date FEB. '78
Engine Curve No. 126

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm × 92.4 mm × 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC NO_x EMISSION BASED ON EGR MODULATION B



RICARDO CONSULTING ENGINEERS

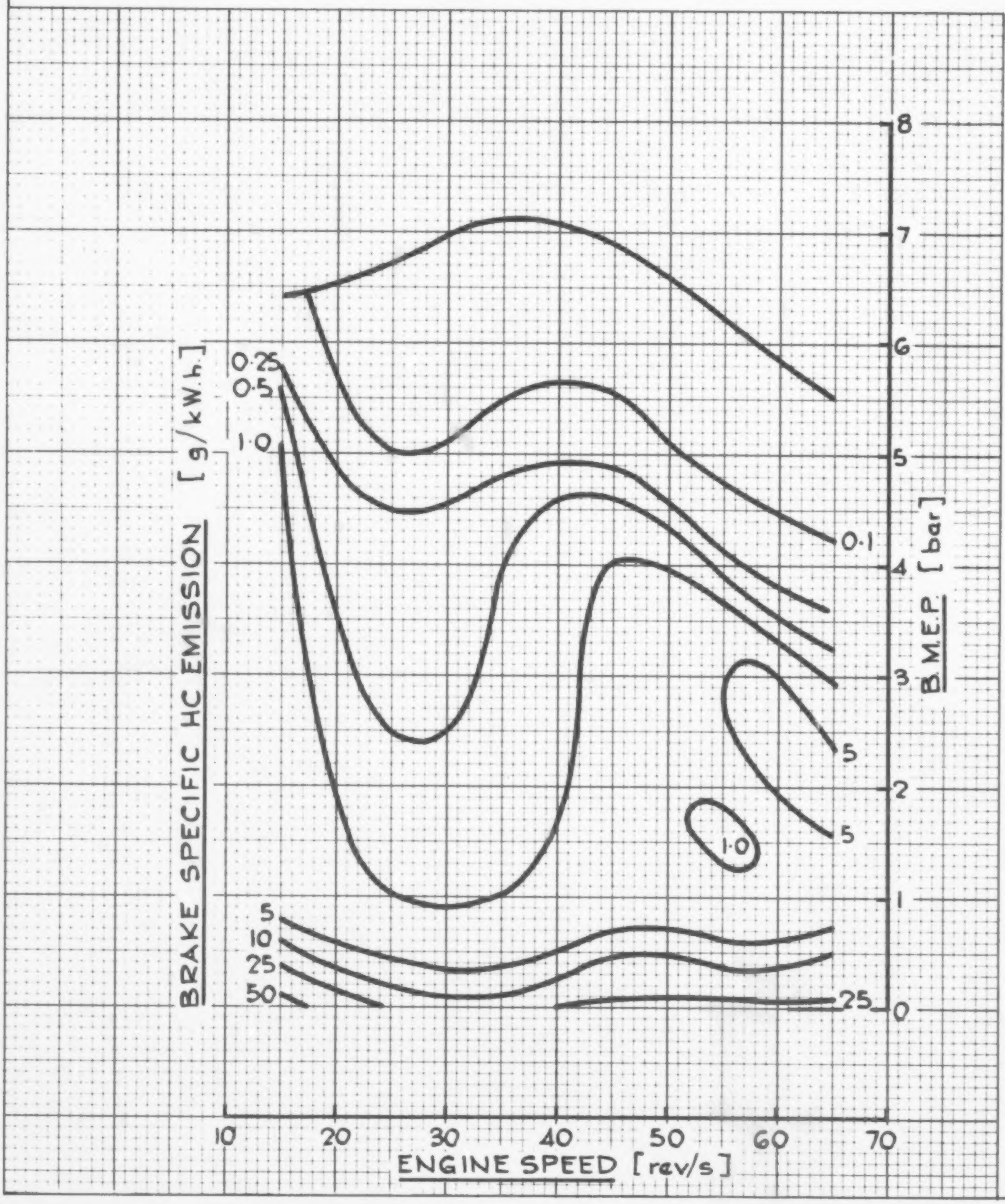
FIG. No. 125
Drg. No. D35015
Date FEB. '78
Engine Curve No. 127

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC HC EMISSION
BASED ON EGR MODULATION B

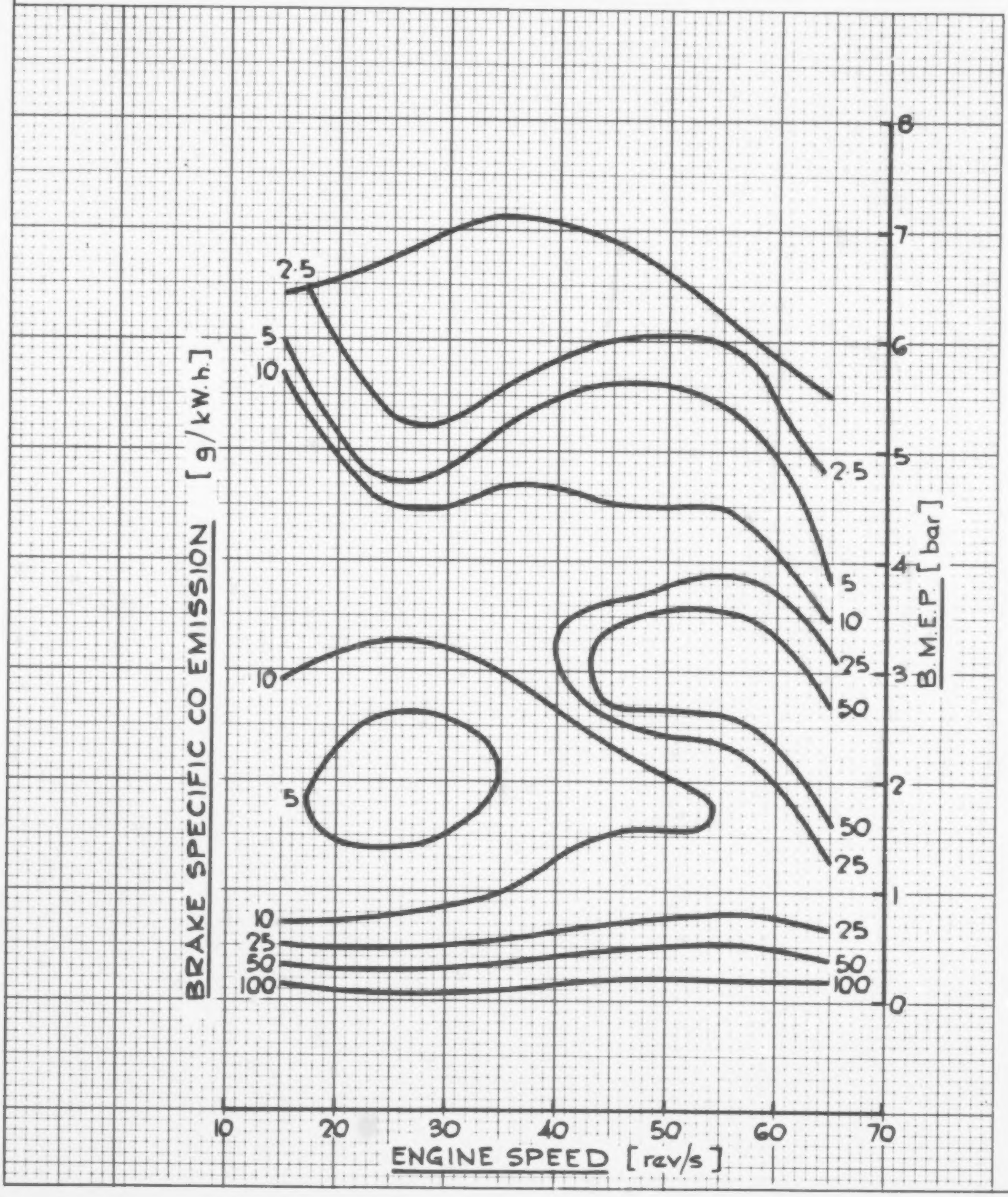


RICARDO CONSULTING ENGINEERS

FIG. No. 126
Drg. No. D35016
Date FEB.'78
Engine Curve No. 128

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC CO EMISSION
BASED ON EGR MODULATION B



RICARDO CONSULTING ENGINEERS

FIG. No. 127

Drg. No. D35017

Date FEB. '78

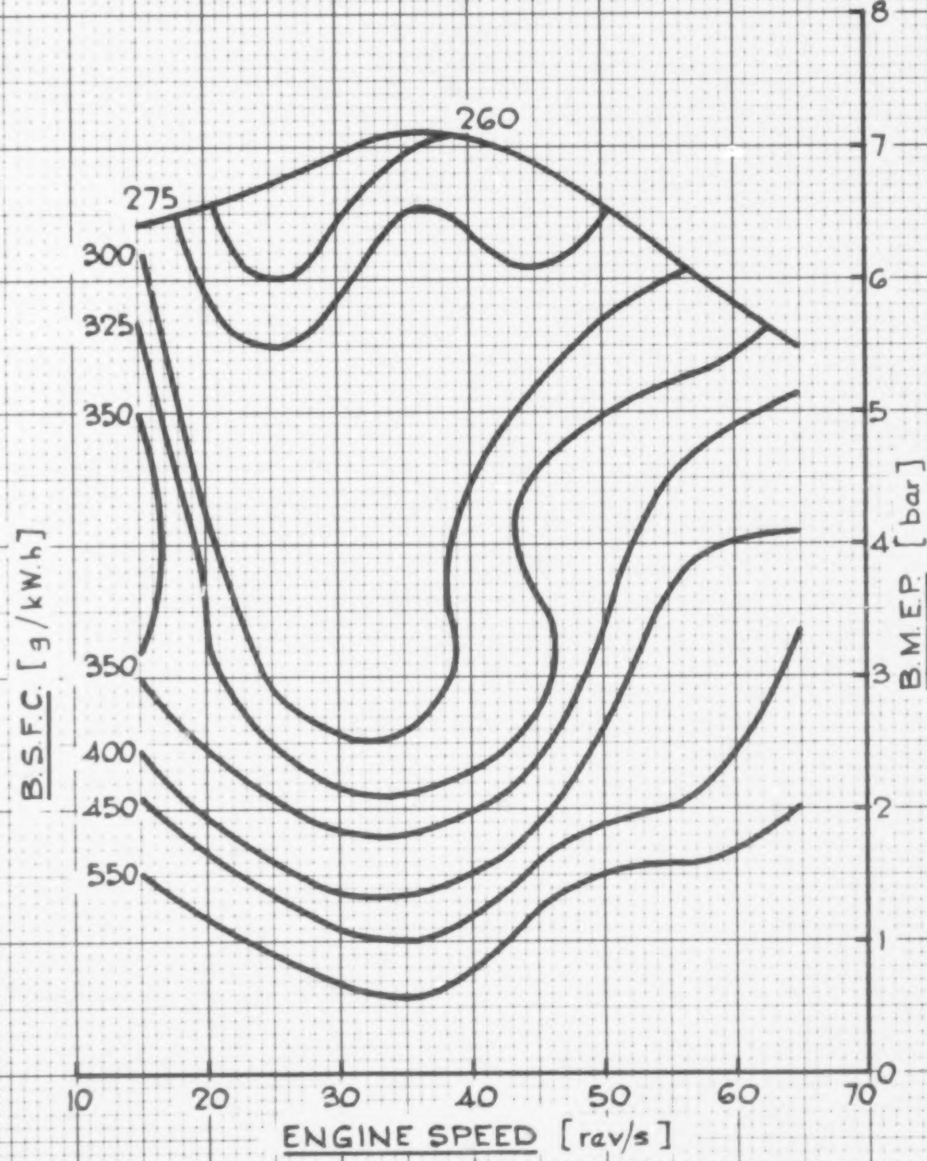
Engine Curve No. 130

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92.4 mm x 5CY'

TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC FUEL CONSUMPTION BASED ON EGR MODULATION B

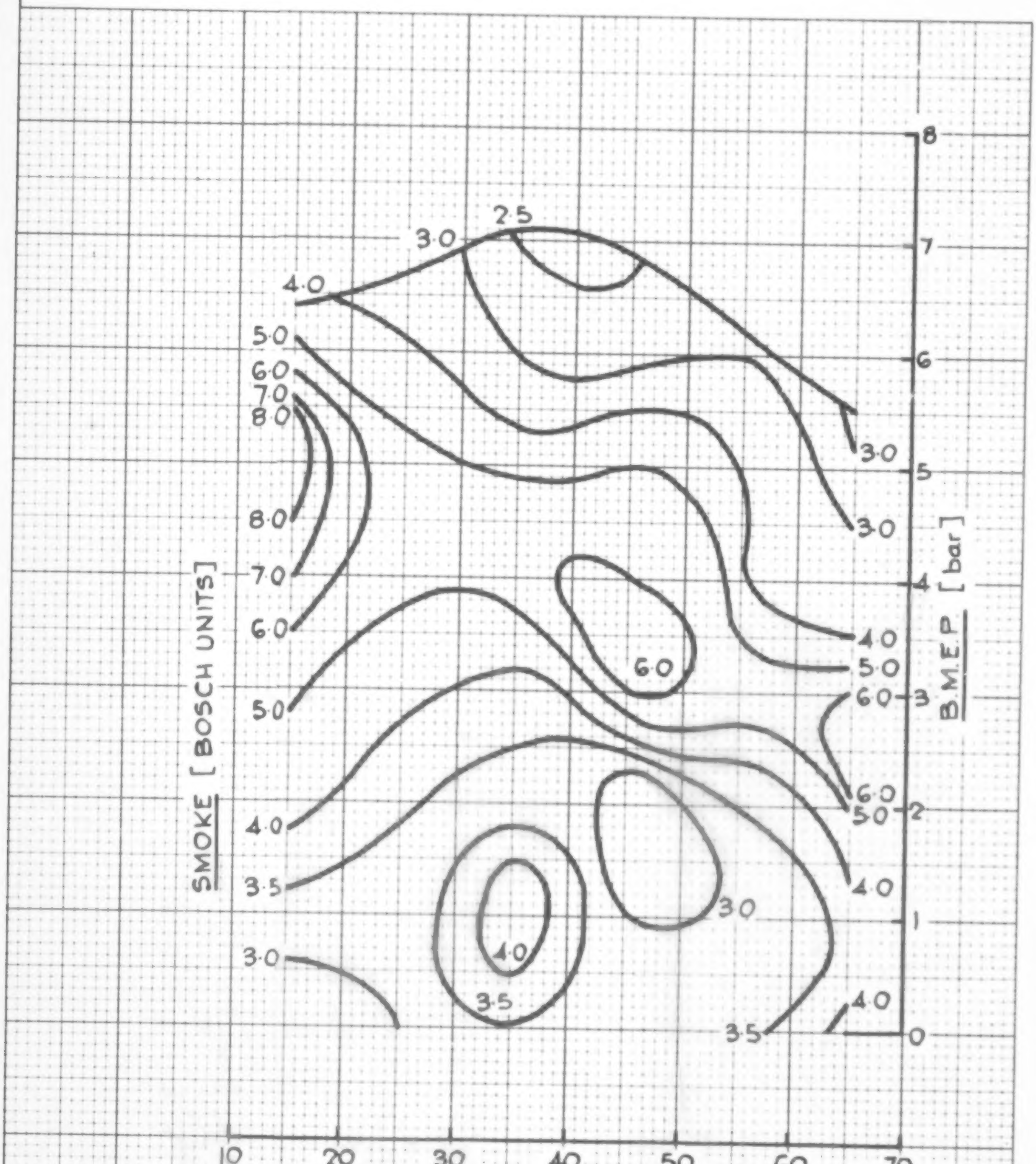


RICARDO CONSULTING ENGINEERS

FIG. No. 128
Drg. No. D35018
Date FEB. '78
Engine Curve No. 132

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm × 92·4 mm × 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF EXHAUST SMOKE DENSITY
BASED ON EGR MODULATION B



RICARDO CONSULTING ENGINEERS

FIG. No. 129
Drg. No. D35019
Date FEB '78
Engine Curve No. 136

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

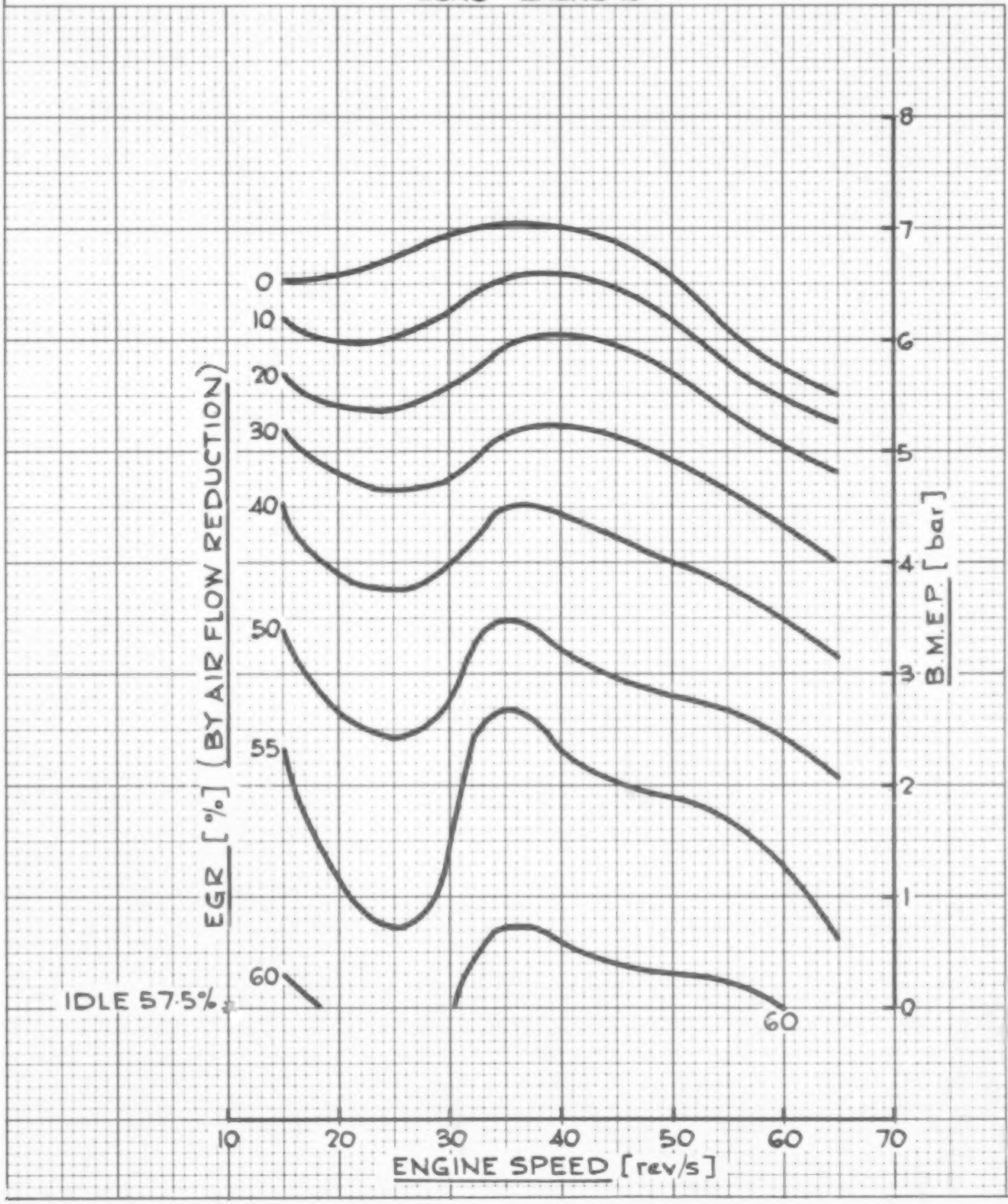
TURBOCHARGED BUILD

COMPOSITE MAP SHOWING EGR MODULATION C

MK. II VALVE N°4 HEAD N°2 SEAT DOWNWARD CLOSING

STATIC SETTINGS: 45·5 mm LIFT AT ZERO RACK
0 mm LIFT AT 100% RACK

ZERO BACKLASH

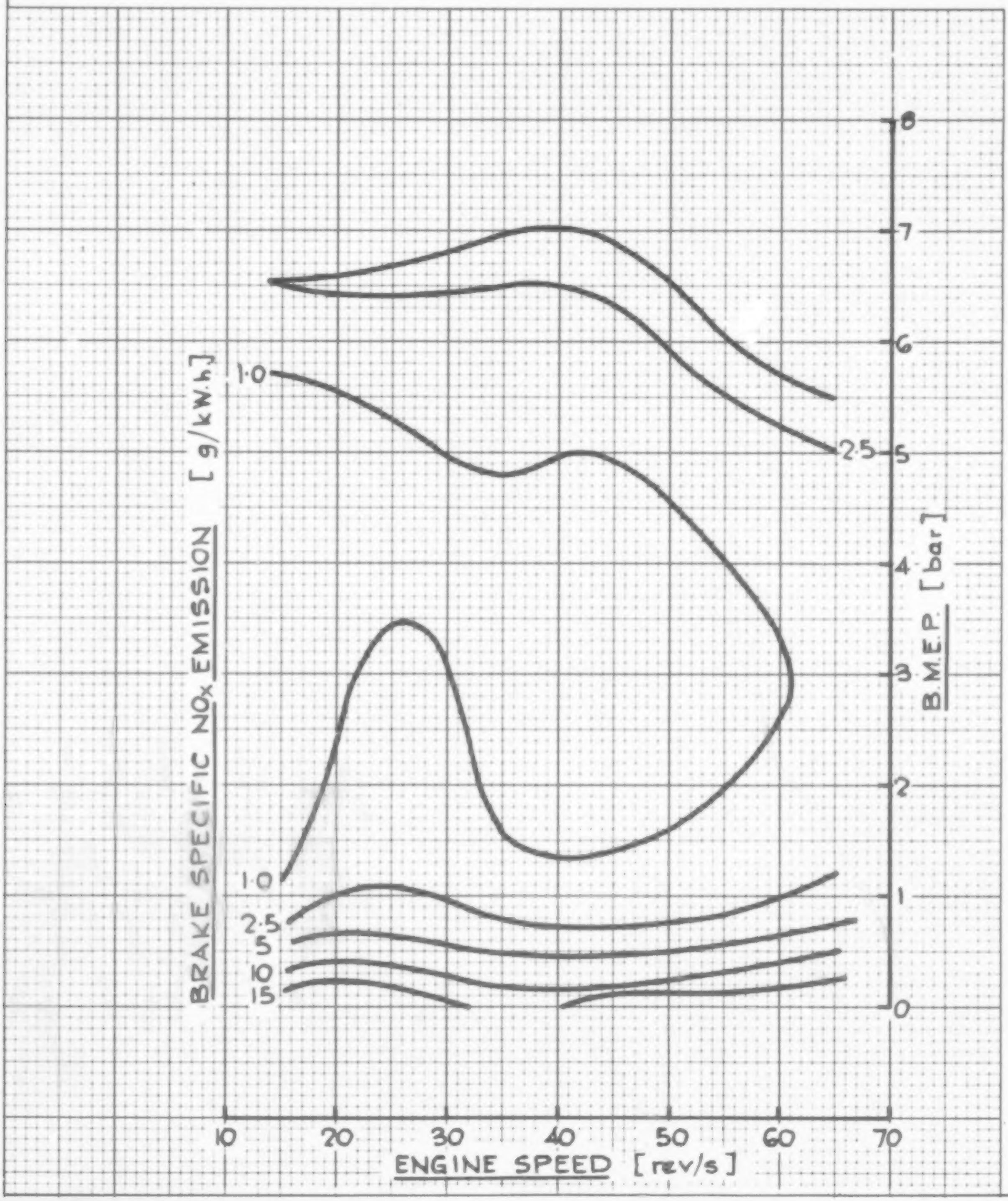


RICARDO CONSULTING ENGINEERS

FIG. No. 130
Drg. No. D35020
Date FEB. '78
Engine Curve No. 143

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC NO_x EMISSION
BASED ON EGR MODULATION C

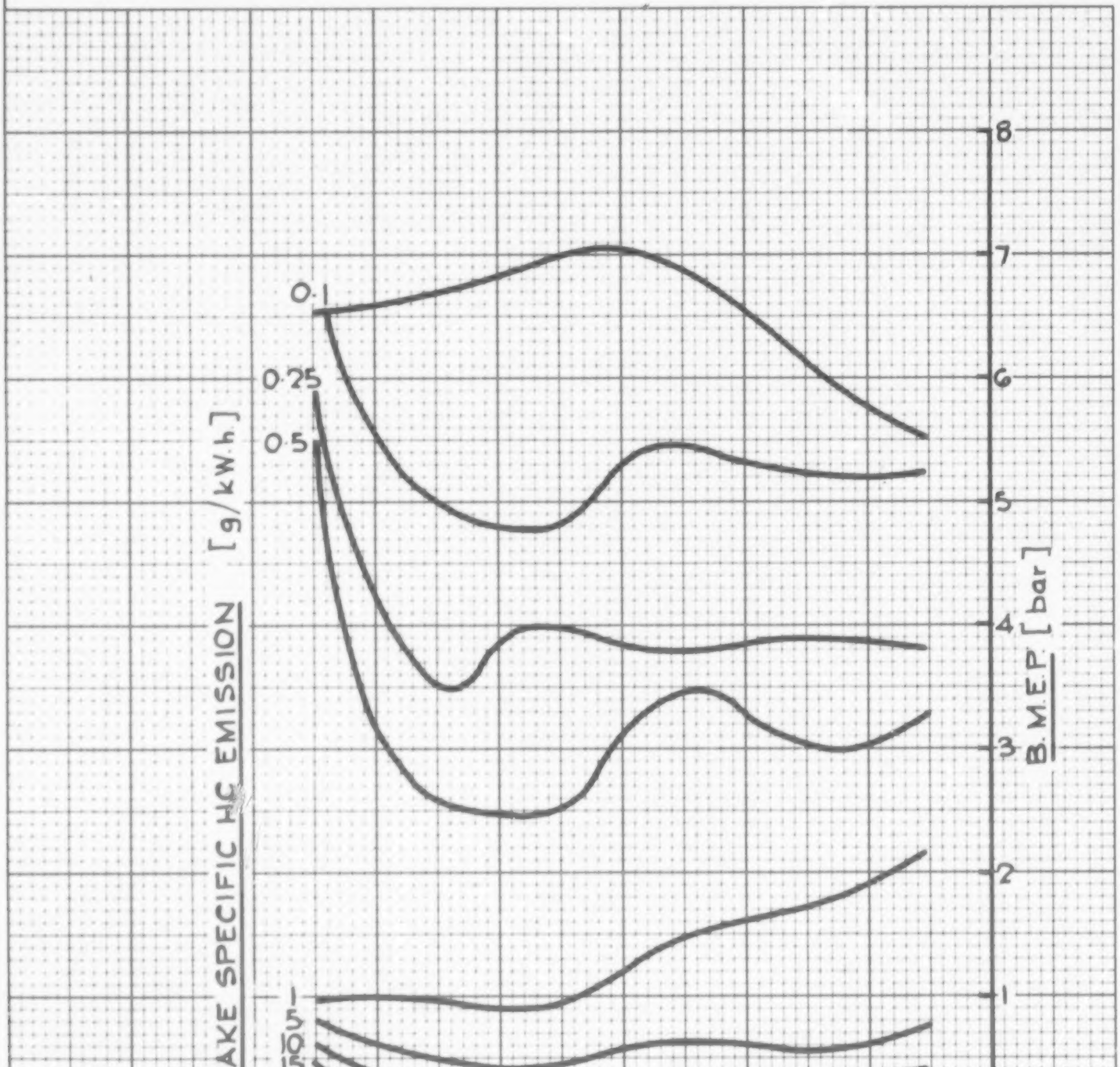


RICARDO CONSULTING ENGINEERS

FIG. No. 131
Drg. No. D35021
Date FEB. '78
Engine Curve No. 144

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm X 92·4 mm X 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC HC EMISSION
BASED ON EGR MODULATION C



RICARDO CONSULTING ENGINEERS

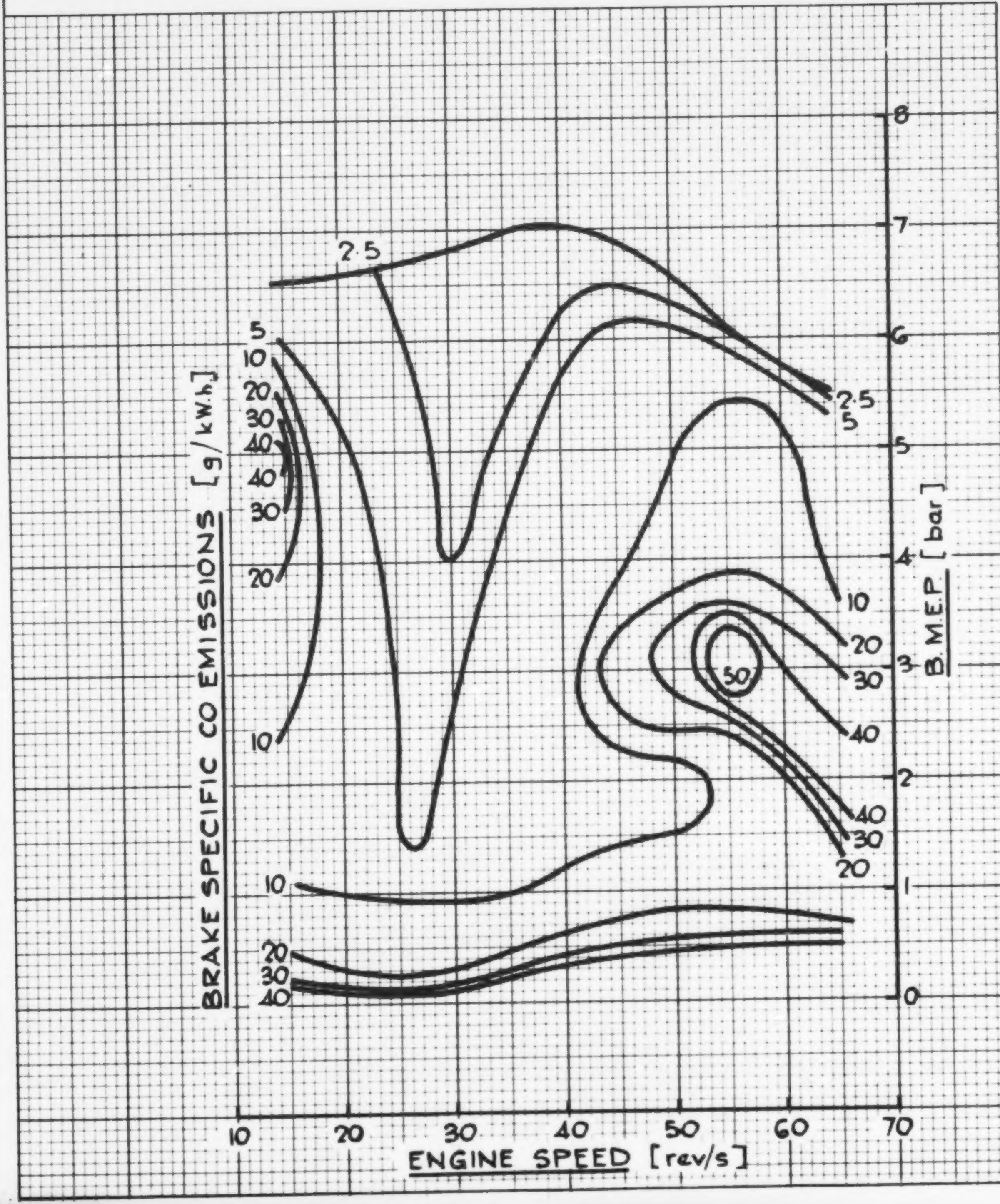
FIG. No. 132
Drg. No. D35022
Date FEB. '78
Engine Curve No. 145

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91mm x 92·4mm x 5CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC CO EMISSIONS
BASED ON EGR MODULATION C



RICARDO CONSULTING ENGINEERS

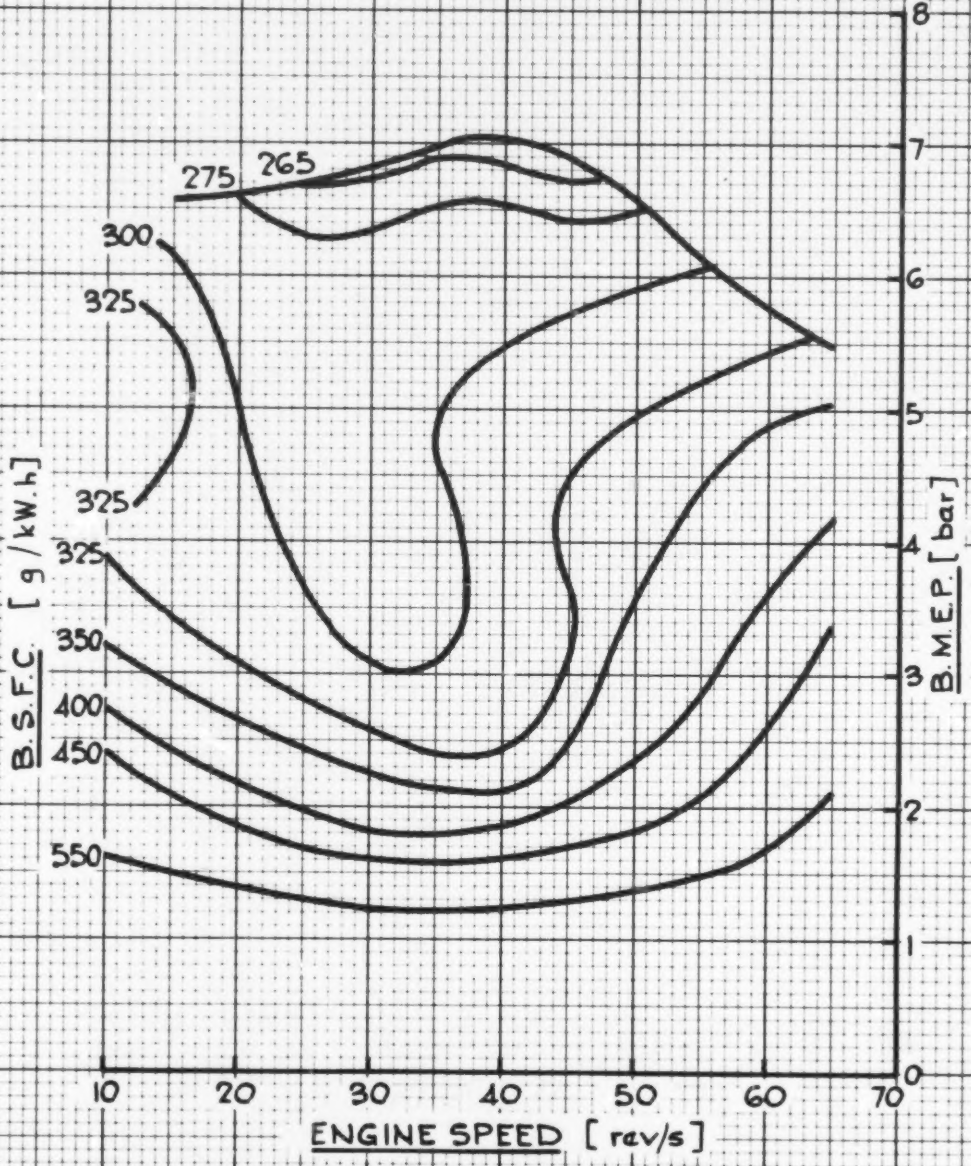
FIG. No. 133
Drg. No. D35023
Date FEB. '78
Engine Curve No. 147

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91mm × 92·4mm × 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC FUEL CONSUMPTION
BASED ON EGR MODULATION C



RICARDO CONSULTING ENGINEERS

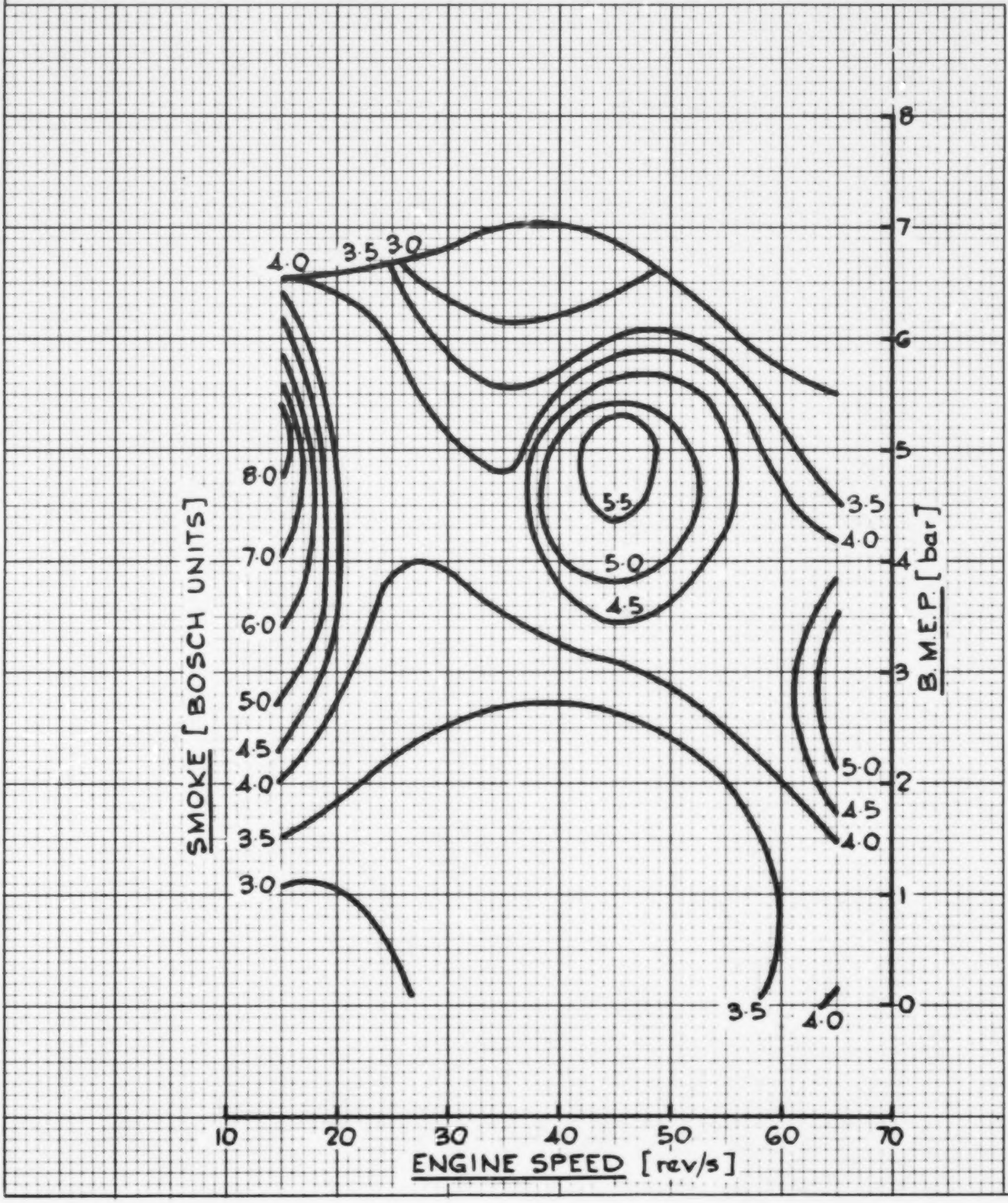
FIG. No. 134
Drg. No. D35024
Date FEB '78
Engine Curve No. 149

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF EXHAUST SMOKE DENSITY
BASED ON EGR MODULATION C



RICARDO CONSULTING ENGINEERS

FIG. No. 135
Drg. No. D35025
Date AUG. '77
Engine Curve No. 153

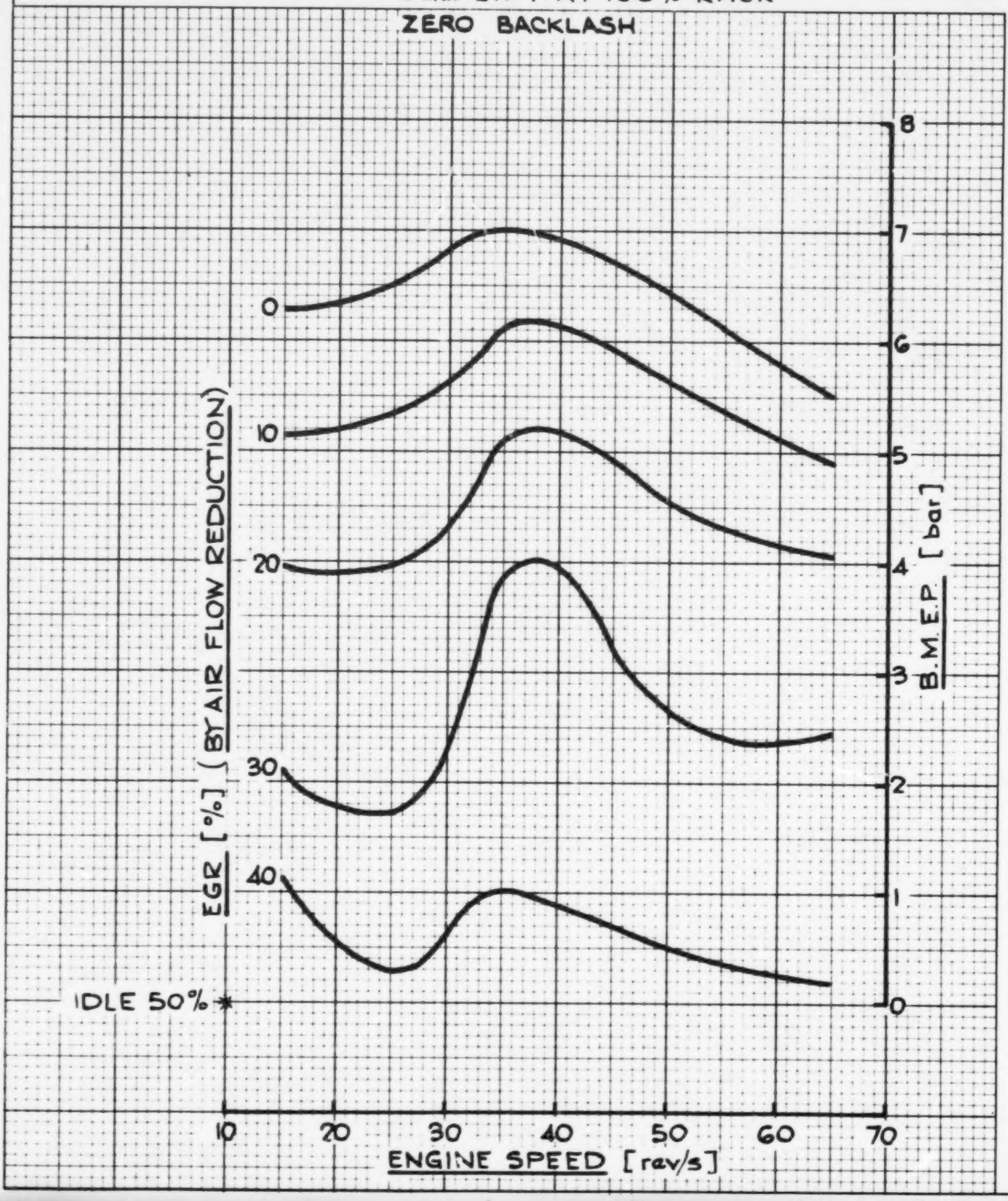
EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm X 92·4 mm X 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP SHOWING EGR MODULATION D
MK. II EGR VALVE N°4 HEAD N°2 SEAT REDUCED LIFT
DOWNWARD CLOSING

STATIC SETTINGS: 17 mm LIFT AT ZERO RACK
0 mm LIFT AT 100% RACK
ZERO BACKLASH



RICARDO CONSULTING ENGINEERS

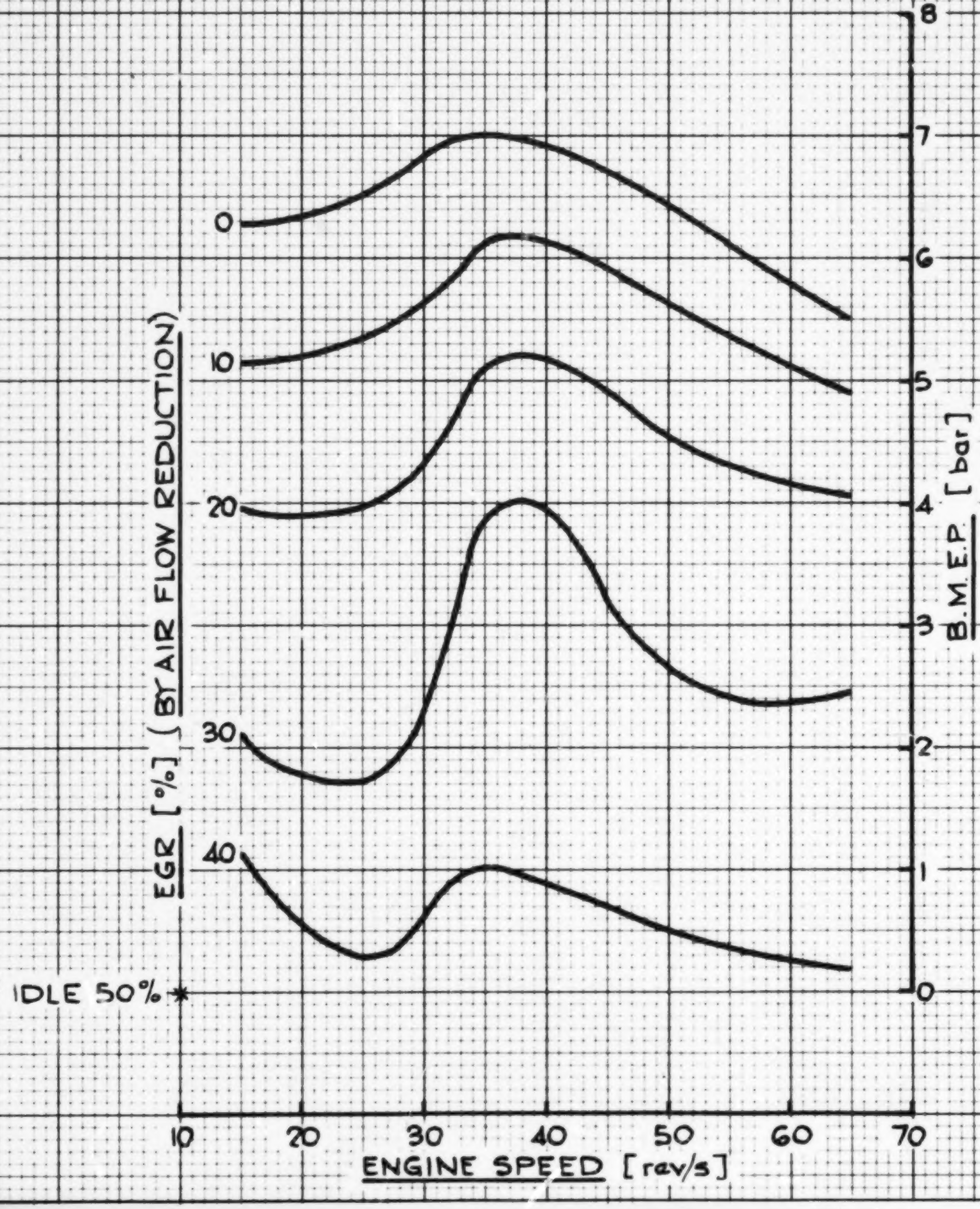
FIG. No. 135
Drg. No. D35025
Date AUG. '77
Engine Curve No. 153

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm X 92·4 mm X 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP SHOWING EGR MODULATION D
MK. II EGR VALVE N°4 HEAD N°2 SEAT REDUCED LIFT
DOWNWARD CLOSING
STATIC SETTINGS: 17 mm LIFT AT ZERO RACK
0 mm LIFT AT 100% RACK
ZERO BACKLASH



RICARDO CONSULTING ENGINEERS

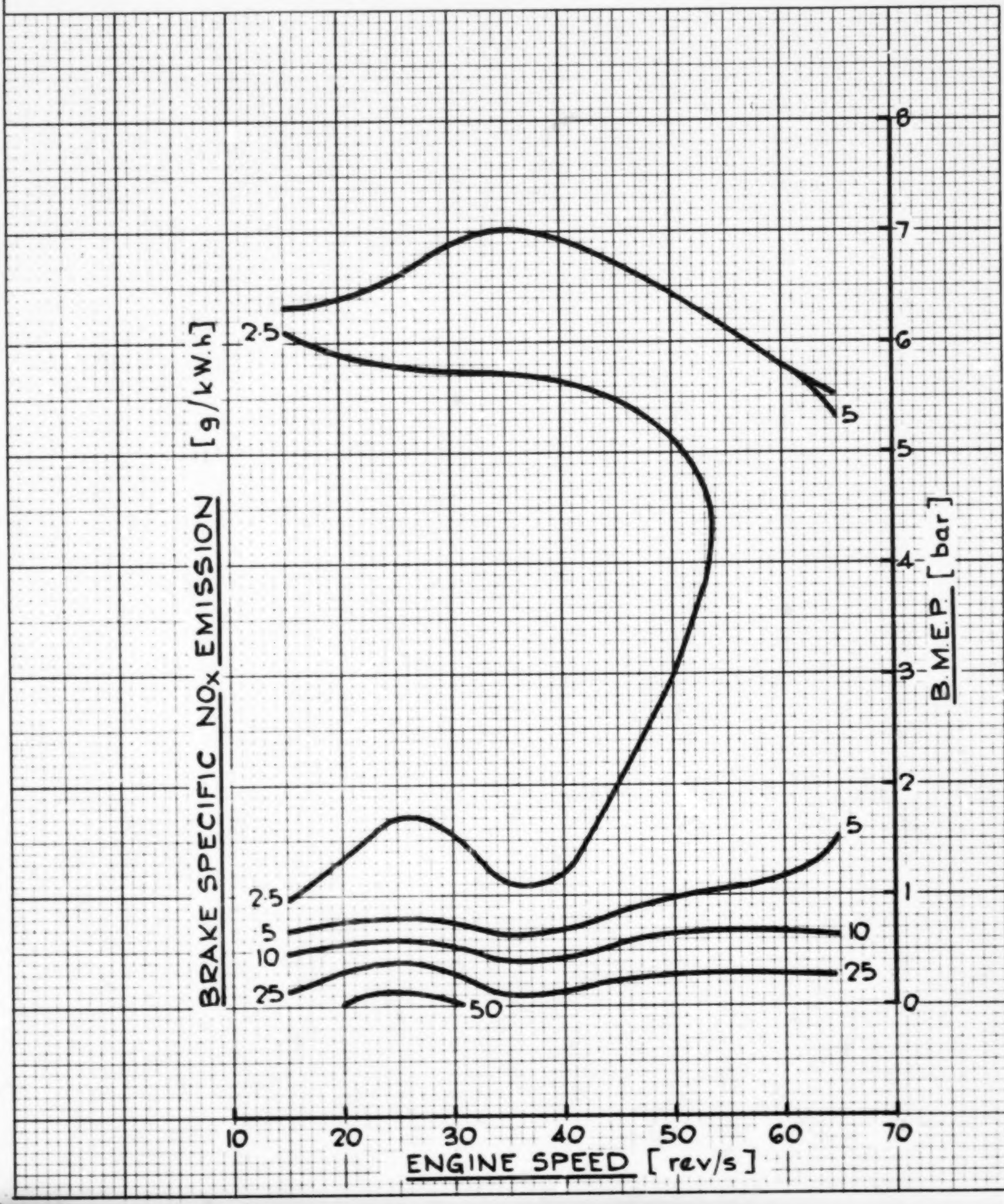
FIG. No. 136
Drg. No. D35026
Date FEB '78
Engine Curve No. 160

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC NO_x EMISSION
BASED ON EGR MODULATION D



RICARDO CONSULTING ENGINEERS

FIG. No. 137

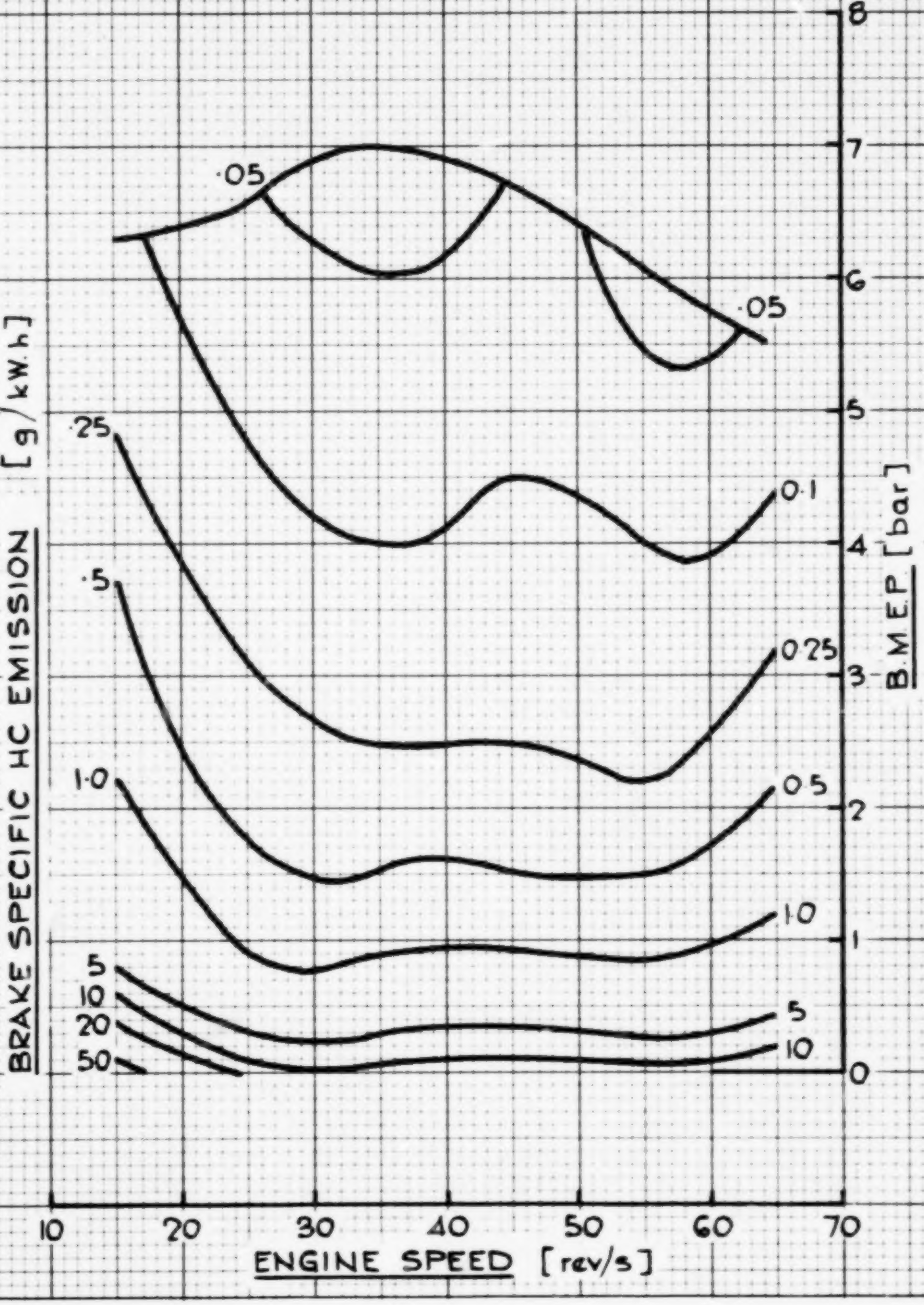
Drg. No. D35027

Date FEB. '78

Engine Curve No. 161

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC HC EMISSION
BASED ON EGR MODULATION D



RICARDO CONSULTING ENGINEERS

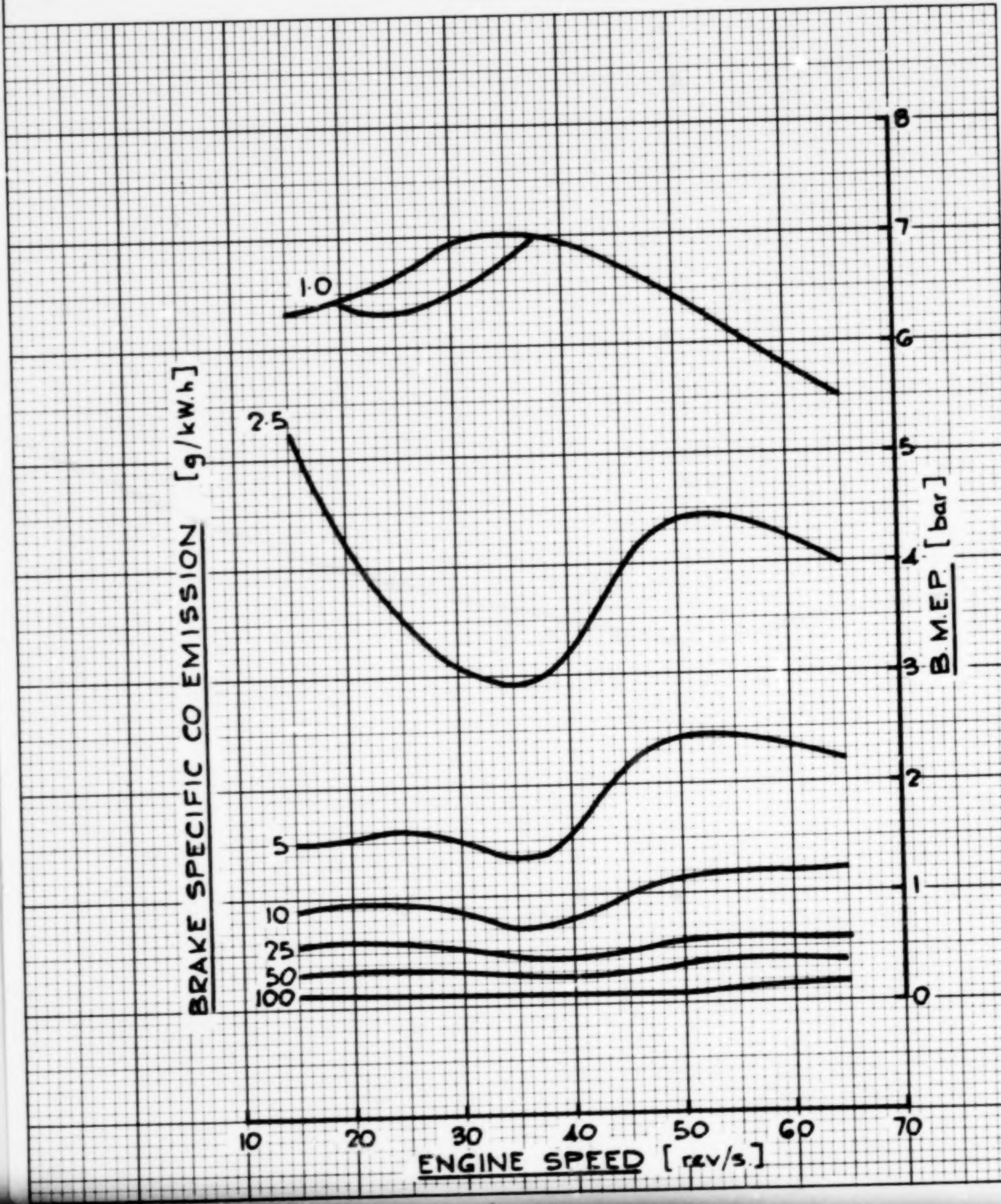
FIG. No. 138
Drg. No. D35028
Date FEB. '78
Engine Curve No. 162

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC CO EMISSION
BASED ON EGR MODULATION D

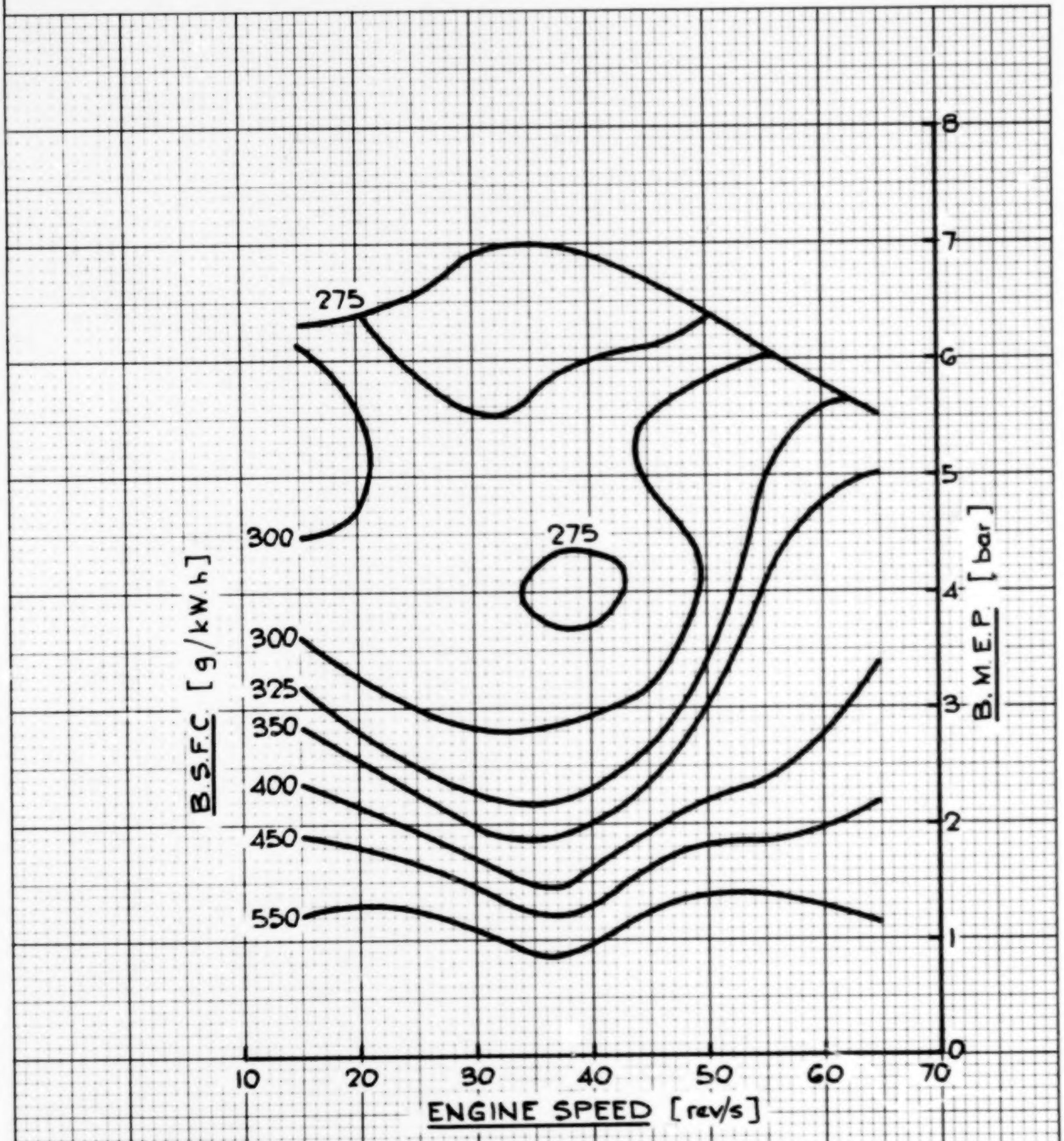


RICARDO CONSULTING ENGINEERS

FIG. No. 139
Drg. No. D35029
Date FEB. '78
Engine Curve No. 164

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92·4mm x 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC FUEL CONSUMPTION
BASED ON EGR MODULATION D

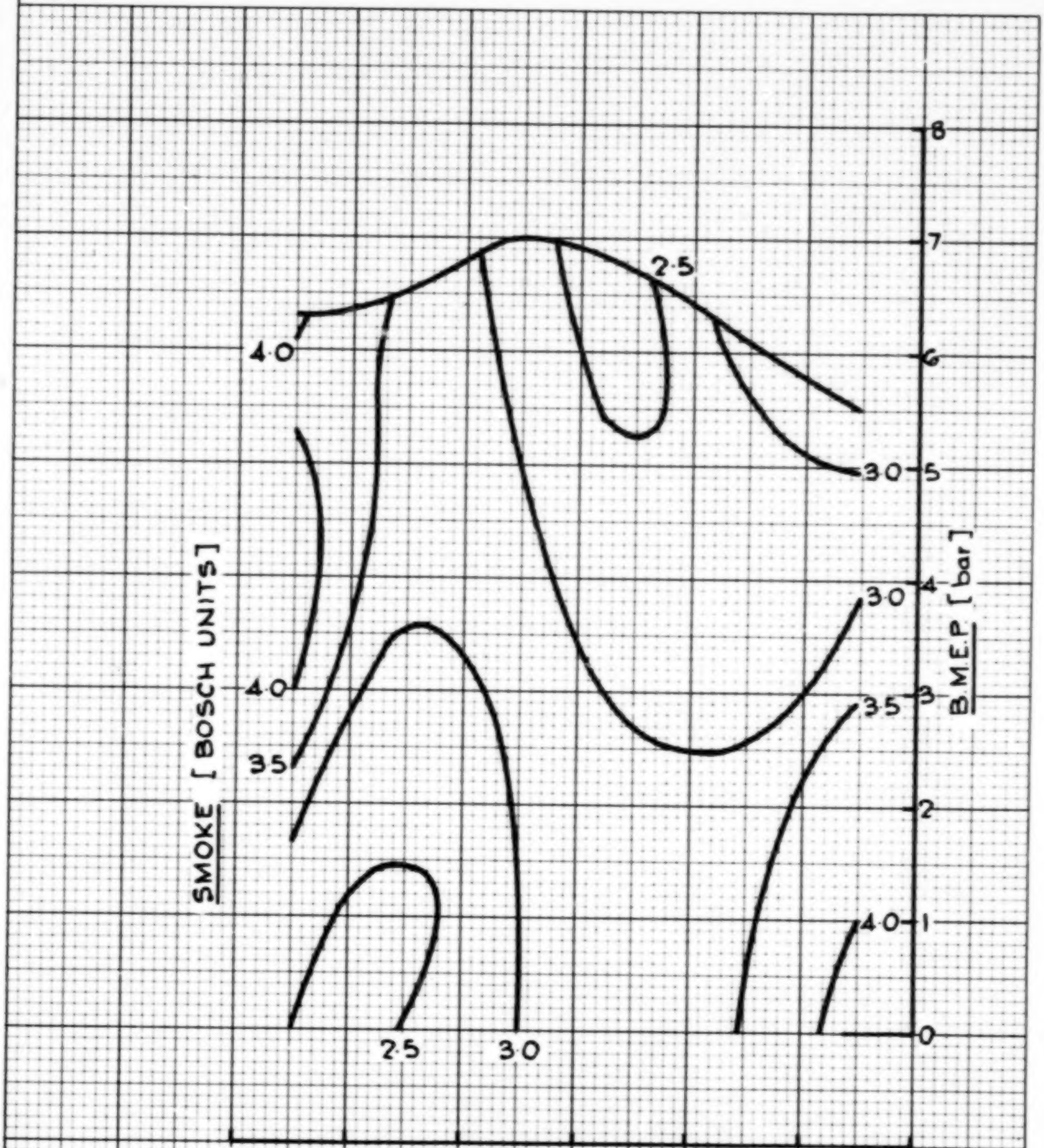


RICARDO CONSULTING ENGINEERS

FIG. No. 140
Drg. No. D35030
Date FEB '78
Engine Curve No. 166

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm × 92·4 mm × 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF EXHAUST SMOKE DENSITY
BASED ON EGR MODULATION D



RICARDO CONSULTING ENGINEERS

FIG. No. 141
Drg. No. D35031
Date FEB '78
Engine Curve No. 169

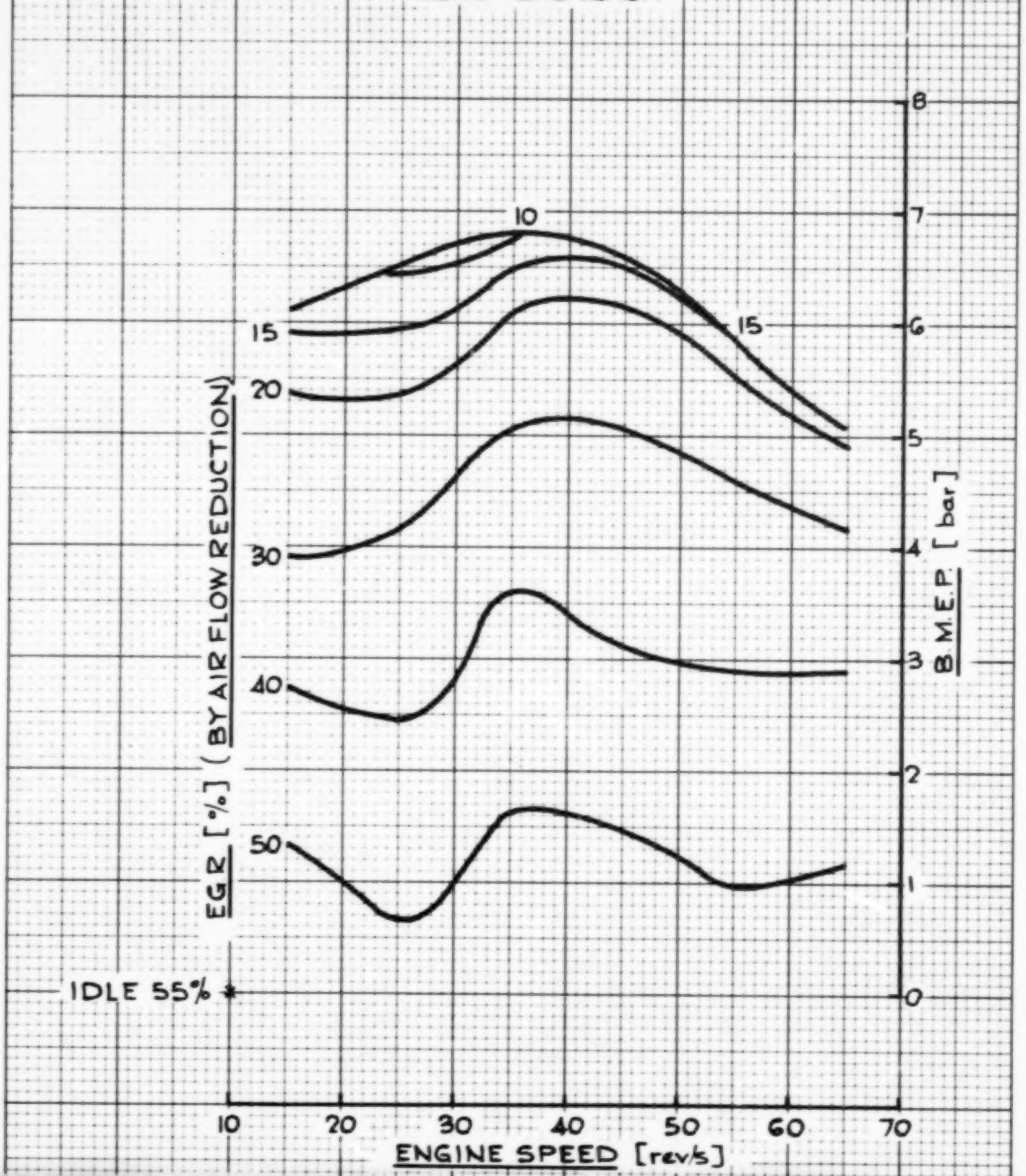
EPA MODULATED EGR STUDY
MERCEDES OMG17 ENGINE 91 mm x 92·4 mm x 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP SHOWING EGR MODULATION E

VALVE BUILD AS FOR MOD. D BUT SOME EGR RETAINED AT FULL LOAD

STATIC SETTINGS : 18·5 mm LIFT AT ZERO RACK
1·5 mm LIFT AT 100% RACK

ZERO BACKLASH

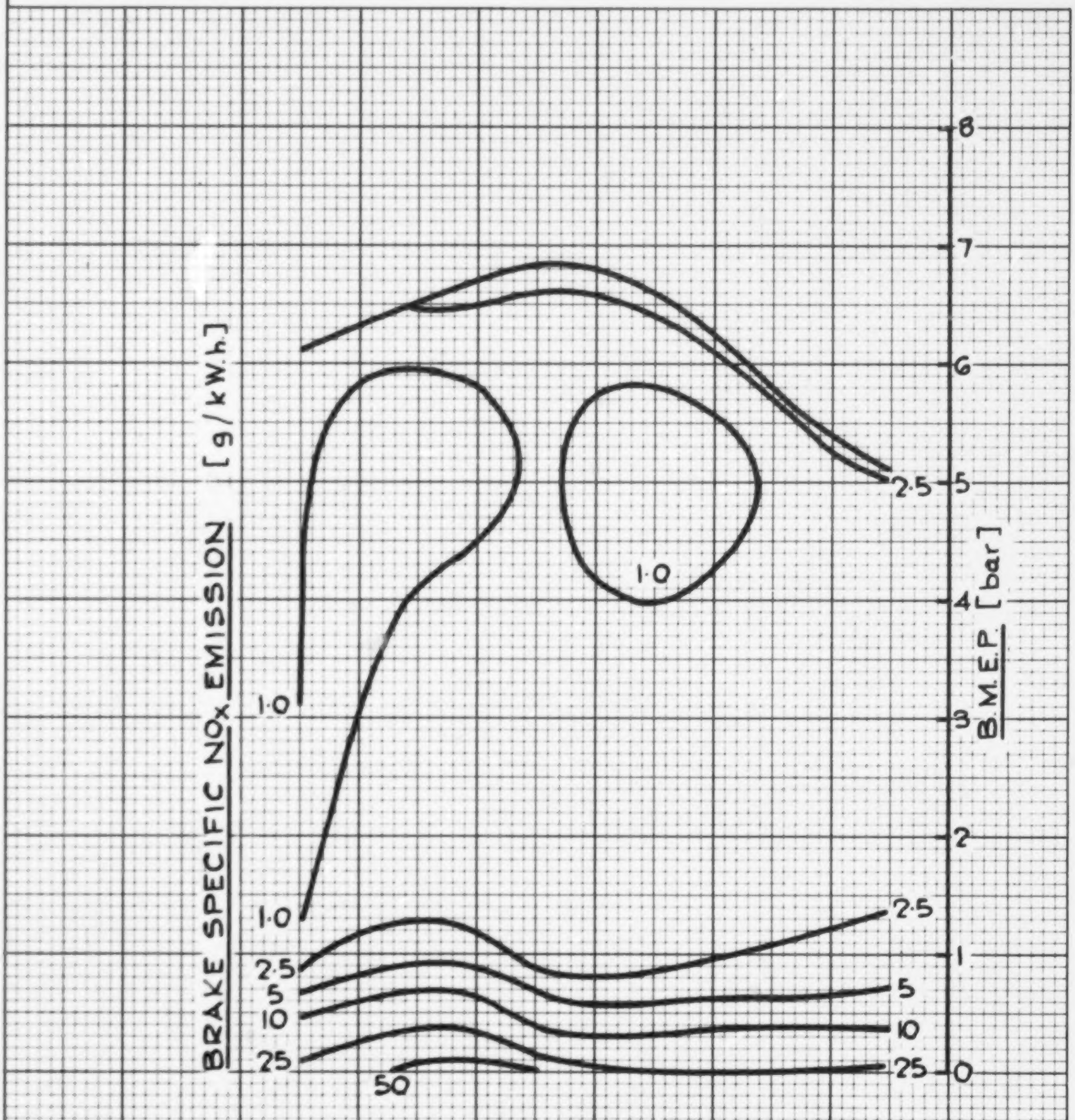


RICARDO CONSULTING ENGINEERS

FIG. No. 142
Drg. No. D35032
Date FEB. '78
Engine Curve No. 176

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91mm x 92·4 mm x 5CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC NO_x EMISSION
BASED ON EGR MODULATION E



RICARDO CONSULTING ENGINEERS

FIG. No. 143

Drg. No. D35033

Date FEB. '78

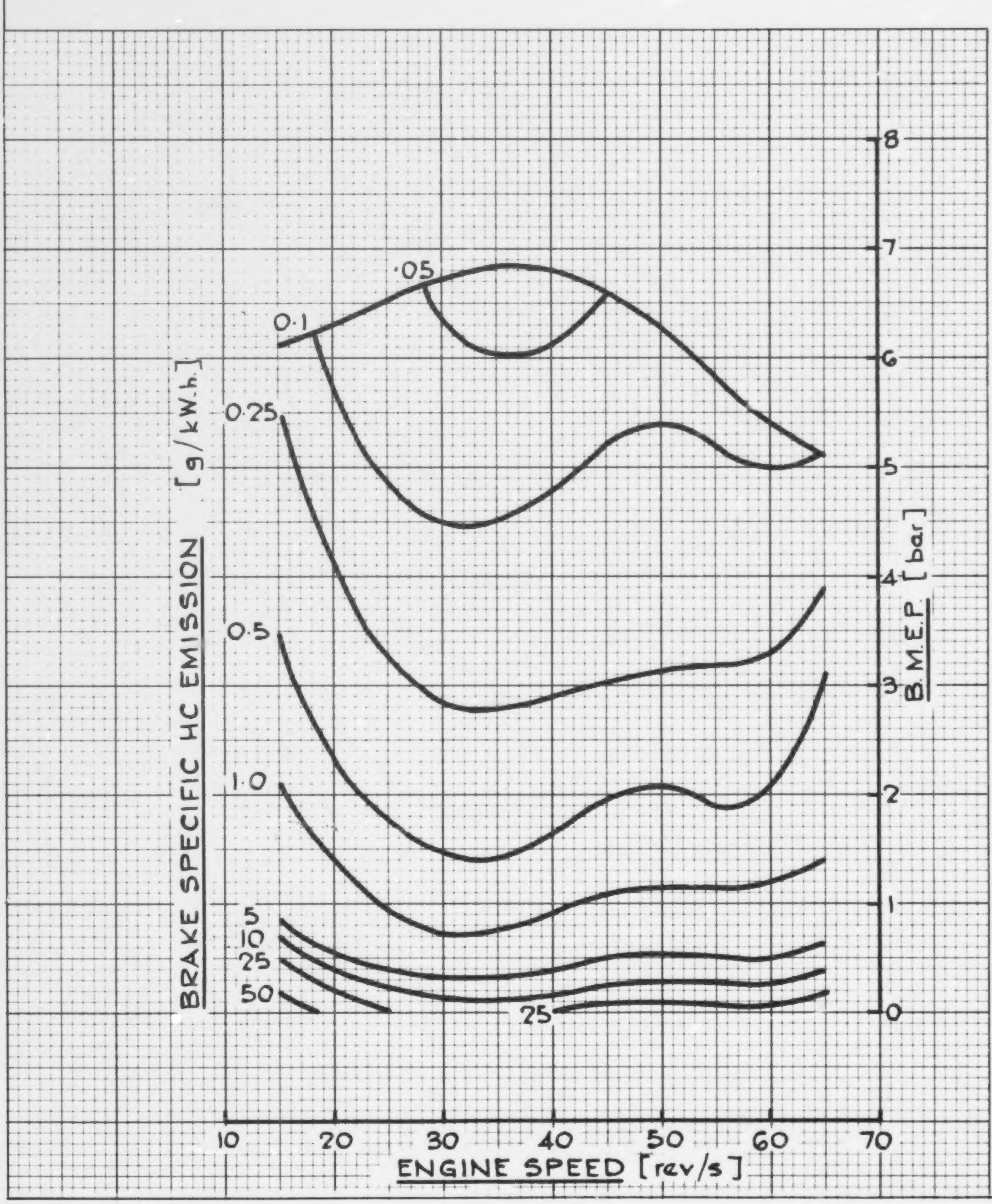
Engine Curve No. 177

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC HC EMISSION
BASED ON EGR MODULATION E

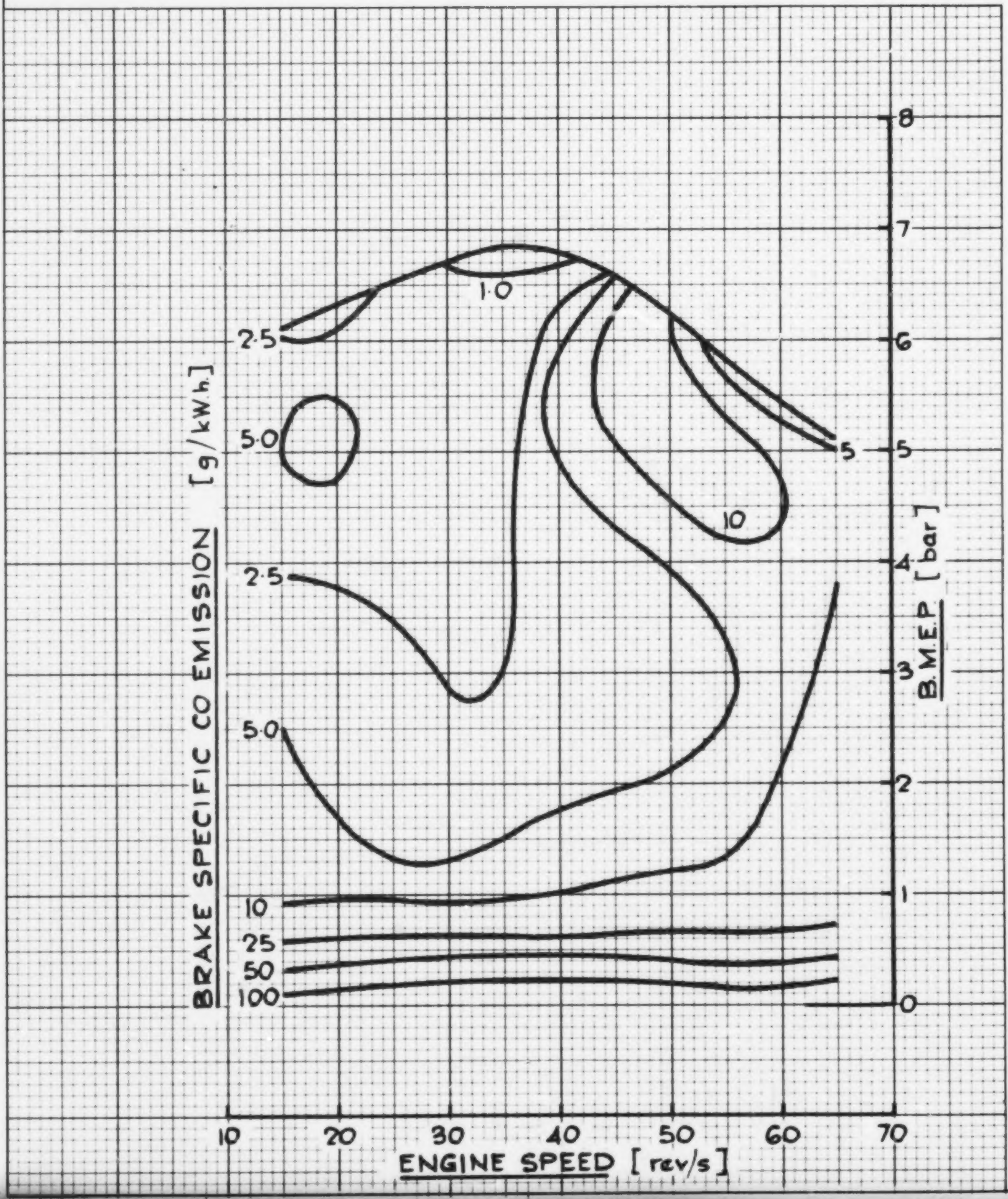


RICARDO CONSULTING ENGINEERS

FIG. No. 144
Drg. No. D35034
Date FEB. '78
Engine Curve No. 178

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC CO EMISSION BASED ON EGR MODULATION E

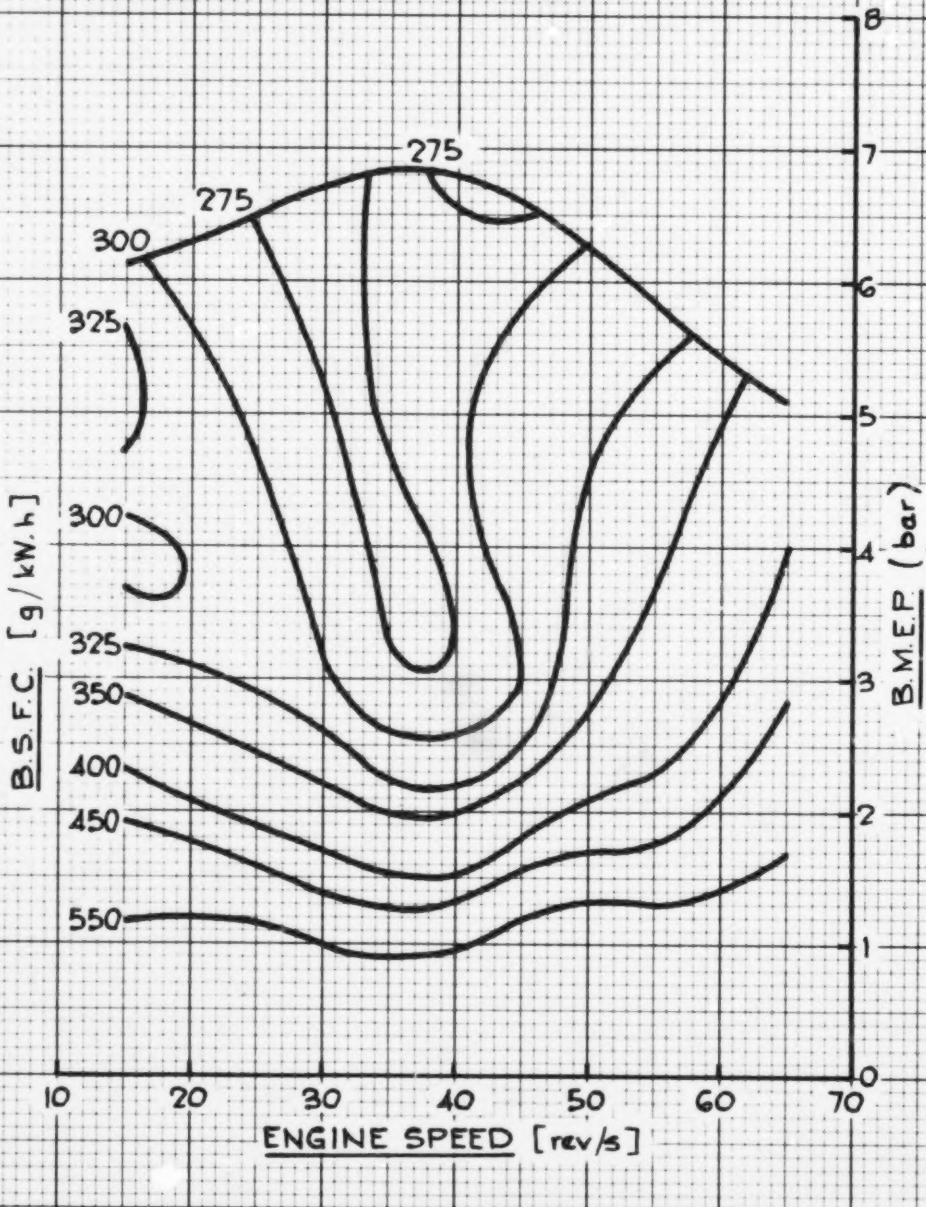


RICARDO CONSULTING ENGINEERS

FIG. No. 145
Drg. No. D35035
Date FEB. '78
Engine Curve No. 180

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC FUEL CONSUMPTION
BASED ON EGR MODULATION E



RICARDO CONSULTING ENGINEERS

FIG. No. 146

Drg. No. D35036

Date FEB. '78

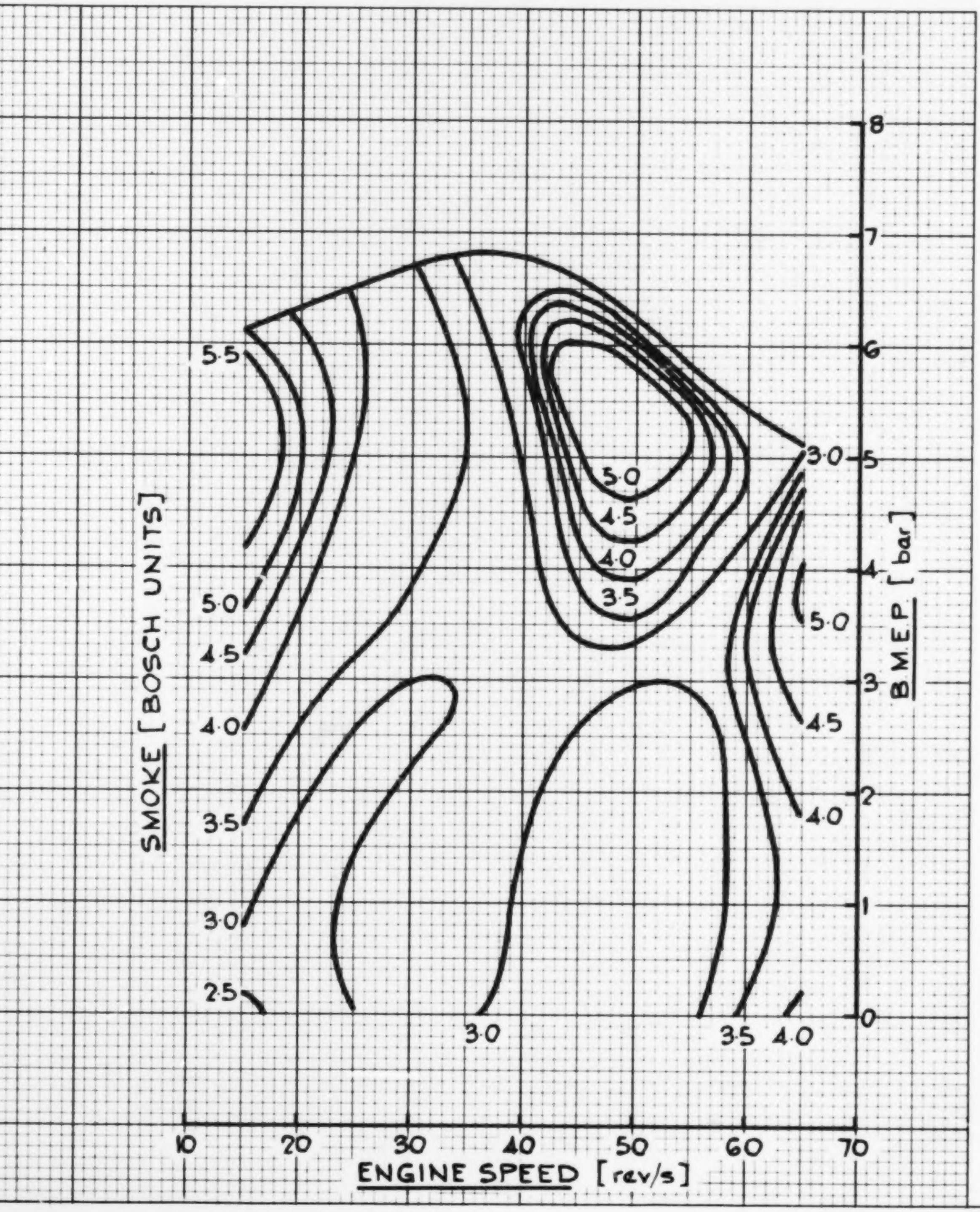
Engine Curve No. 182

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92.4 mm x 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF EXHAUST SMOKE DENSITY
BASED ON EGR MODULATION E



RICARDO CONSULTING ENGINEERS

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

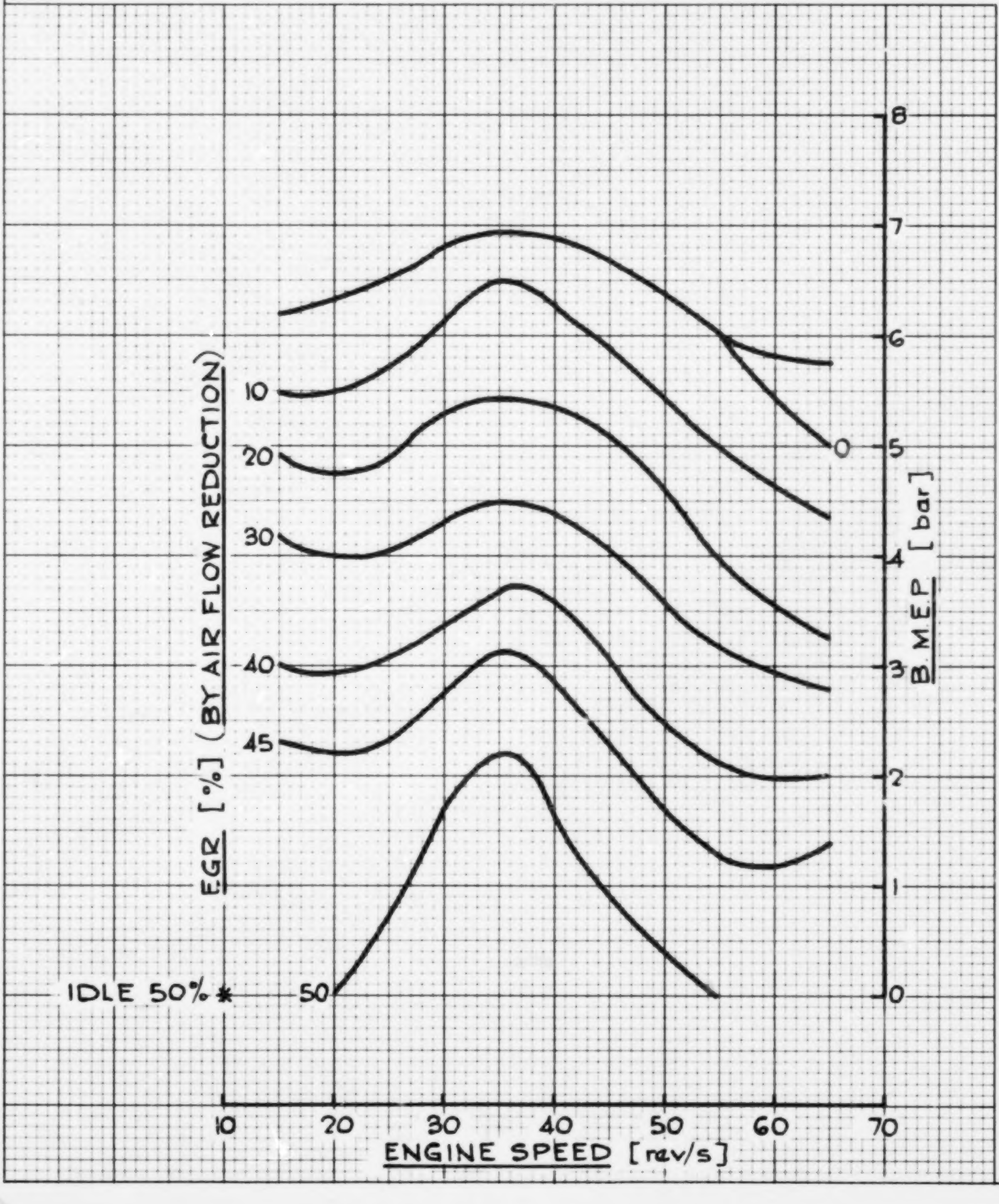
TURBOCHARGED BUILD

FIG. No. 147
Drg. No. D35037
Date FEB '78
Engine Curve No. 185

COMPOSITE MAP SHOWING EGR MODULATION F

MK. II VALVE Nº 2A HEAD Nº 1 SEAT UPWARD CLOSING

STATIC SETTINGS: 23 mm LIFT AT ZERO RACK
0 mm LIFT AT 100% RACK
2 mm BACKLASH (PRESSURE MODULATION)

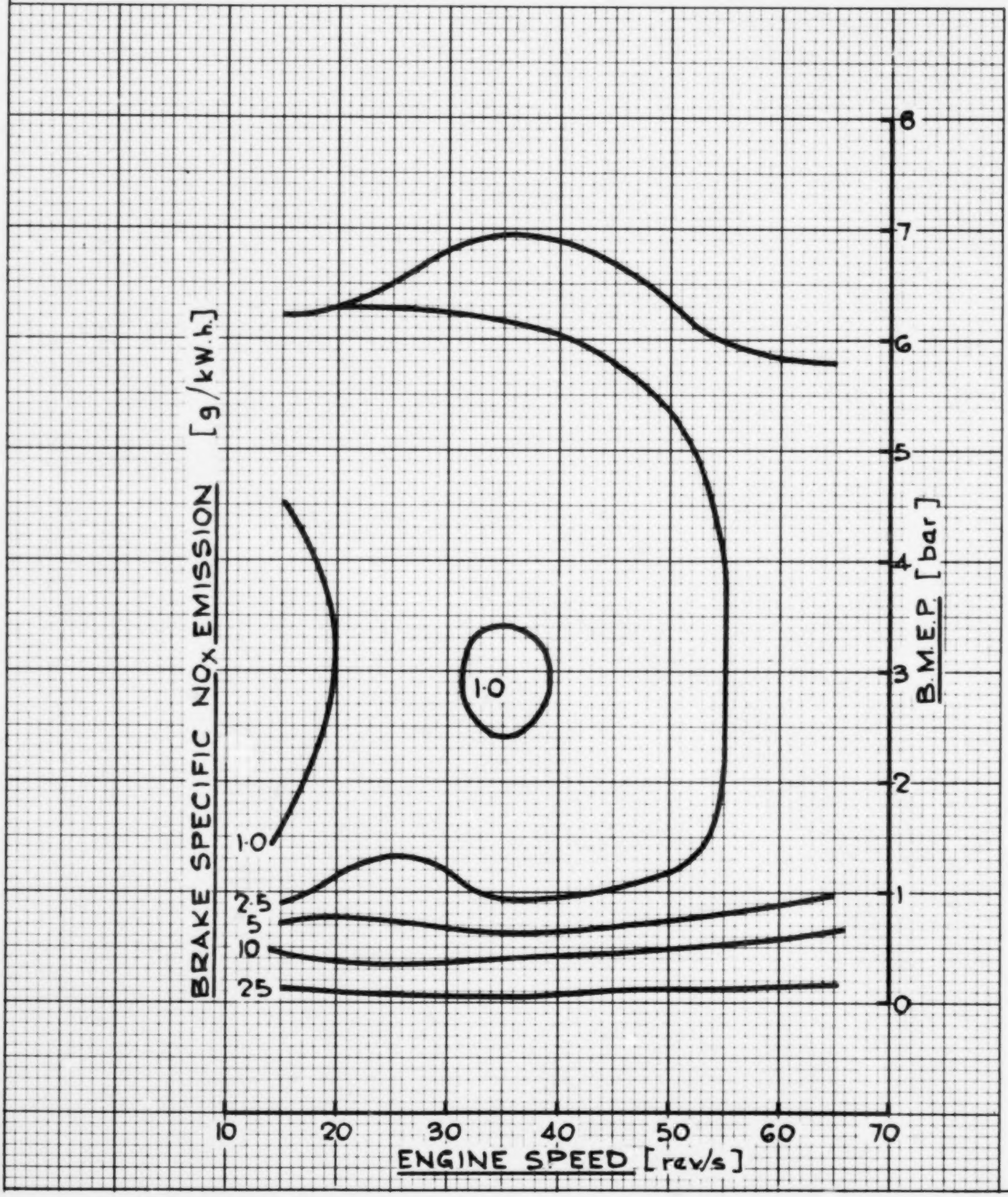


RICARDO CONSULTING ENGINEERS

FIG. No. 148
Drg. No. D35038
Date FEB. '78
Engine Curve No. 192

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC NO_x EMISSION BASED ON EGR MODULATION F



RICARDO CONSULTING ENGINEERS

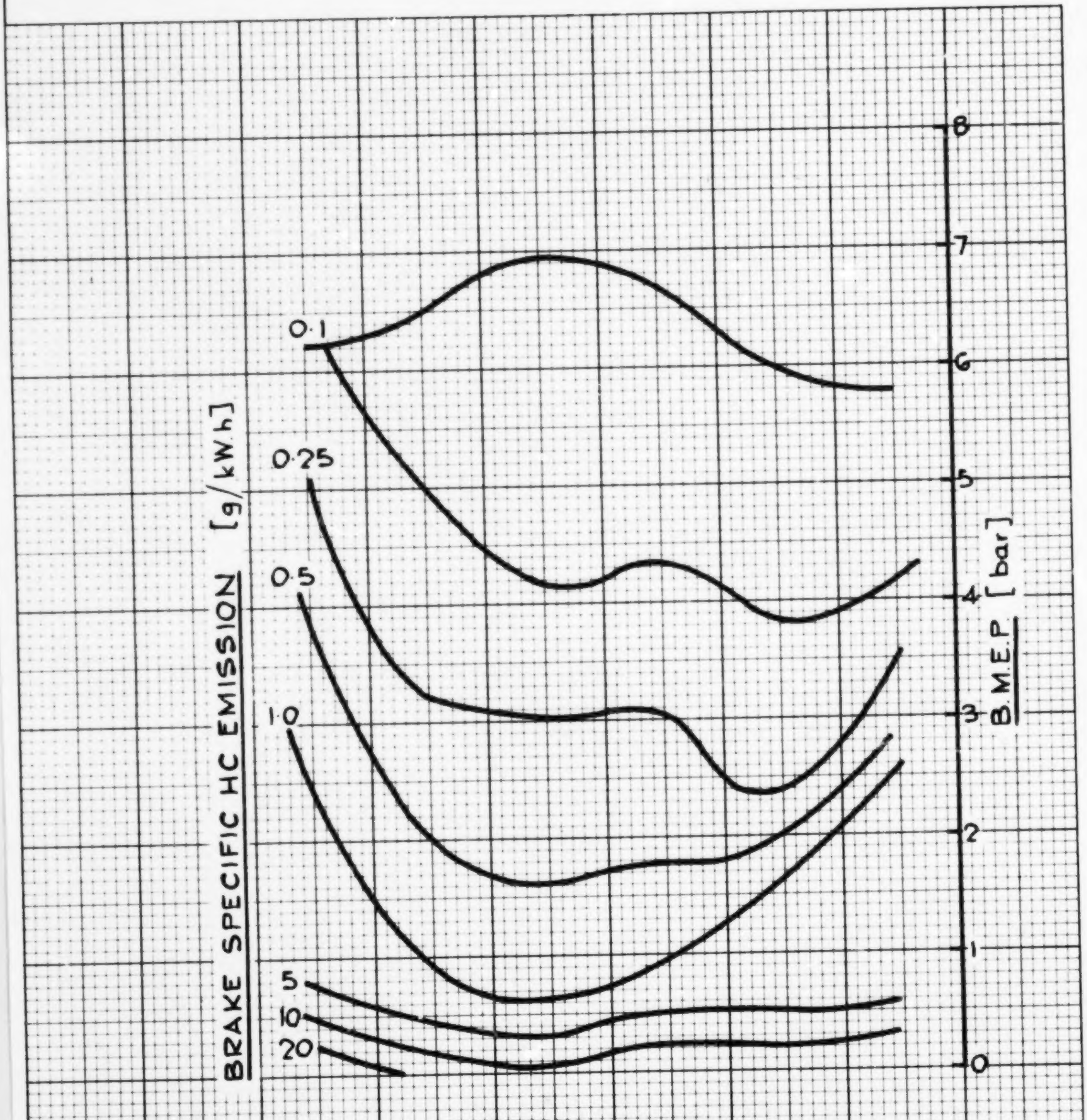
FIG. No. 149
Drg. No. D35039
Date FEB. '78
Engine Curve No. 193

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC HC EMISSION
BASED ON EGR MODULATION F



RICARDO CONSULTING ENGINEERS

FIG. No. 150

Drg. No. D35040

Date FEB. '78

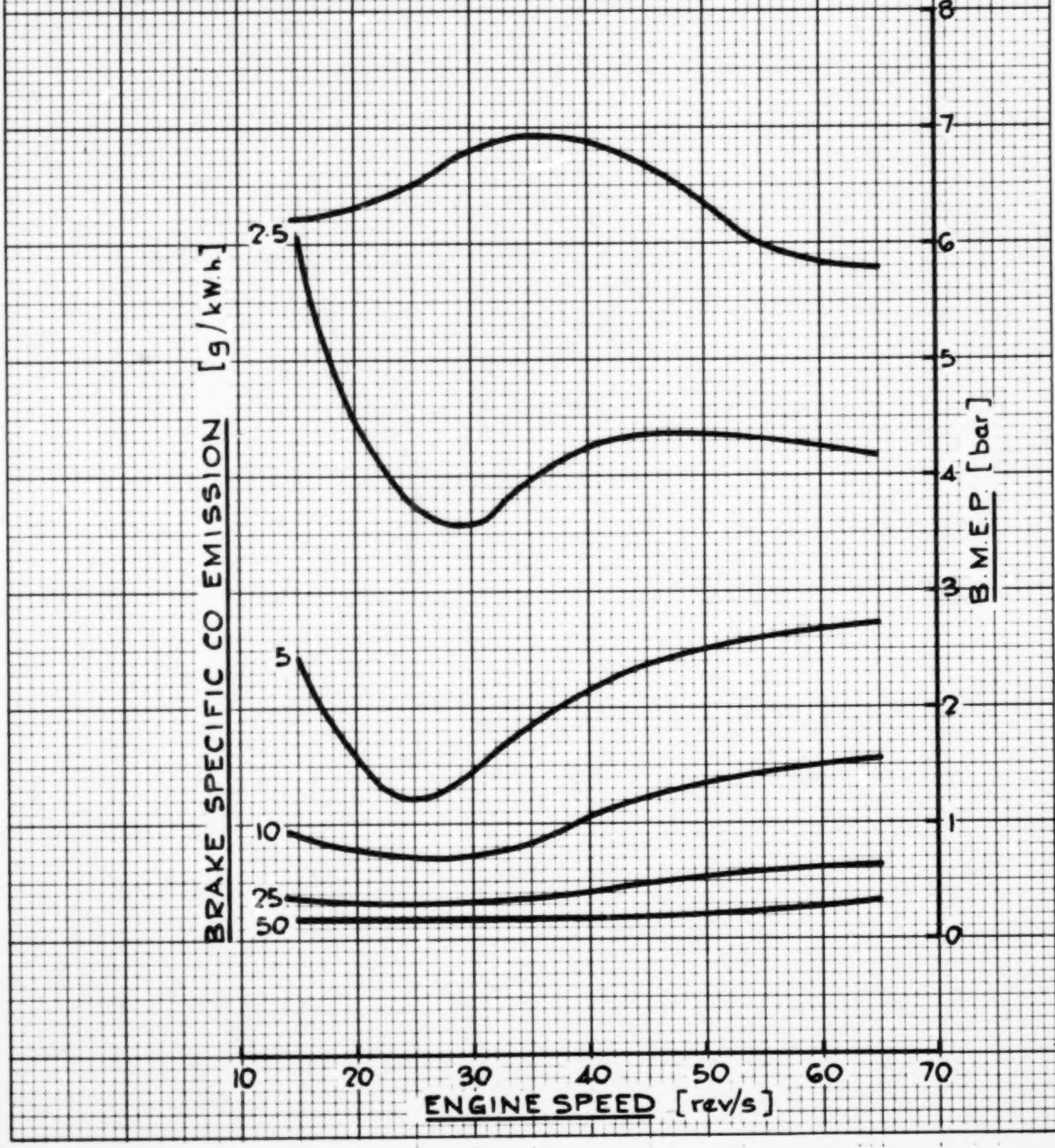
Engine Curve No. 194

EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC CO EMISSION
BASED ON EGR MODULATION F

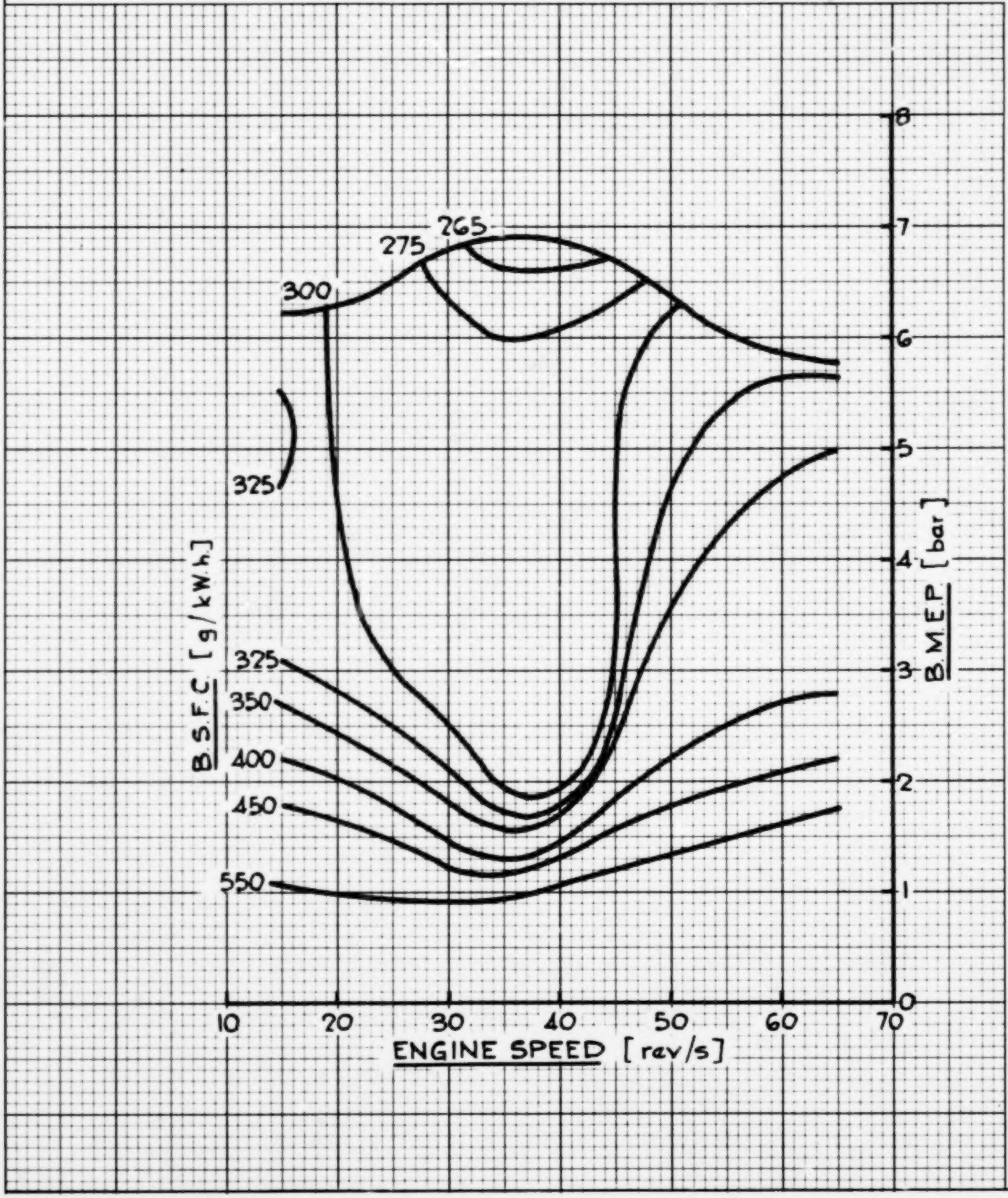


RICARDO CONSULTING ENGINEERS

FIG. No. 151
Drg. No. D35041
Date FEB. '78
Engine Curve No. 196

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5 CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC FUEL CONSUMPTION
BASED ON EGR MODULATION F



RICARDO CONSULTING ENGINEERS

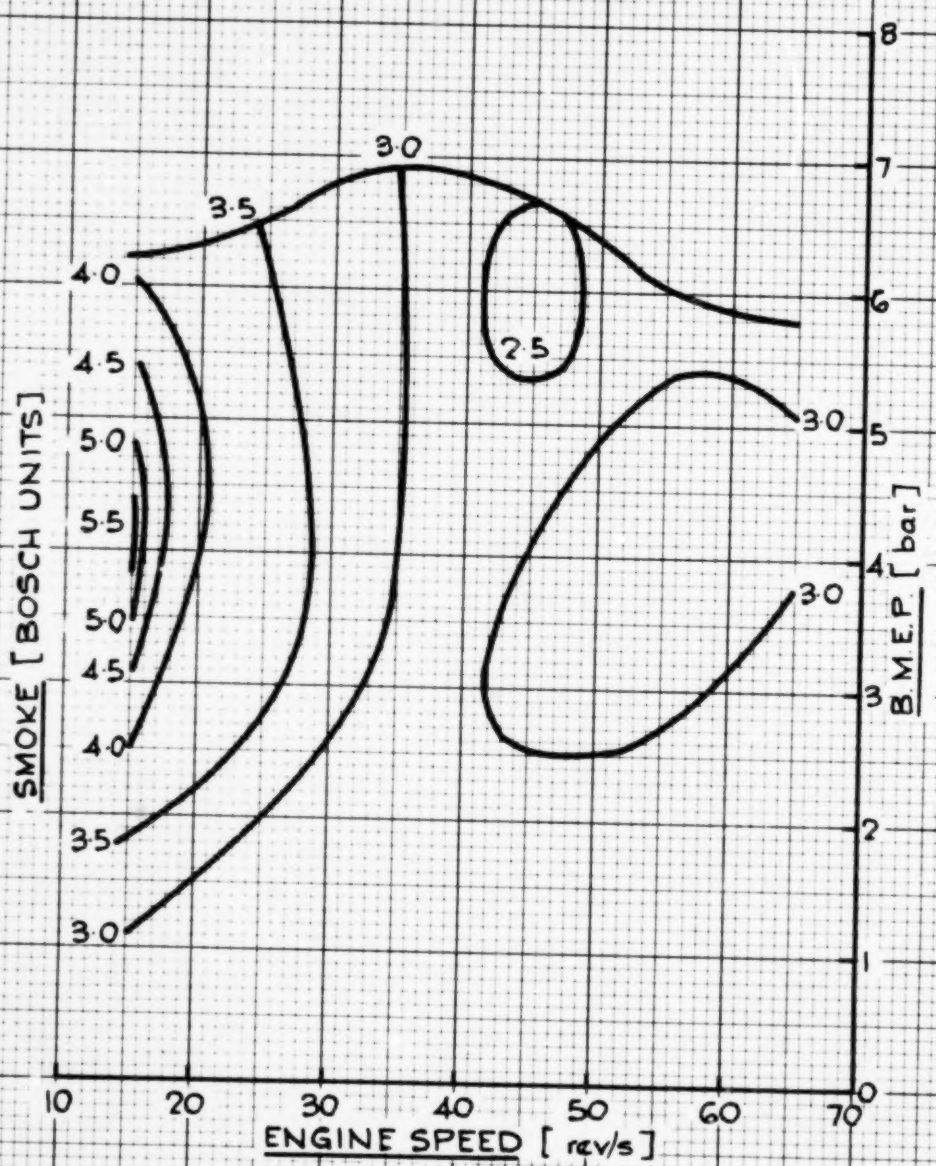
FIG. No. 152
Drg. No. D35042
Date FEB.'78
Engine Curve No. 198

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF EXHAUST SMOKE DENSITY
BASED ON EGR MODULATION F



RICARDO CONSULTING ENGINEERS

FIG. No. 153
Drg. No. D35043
Date FEB. '78
Engine Curve No. 201

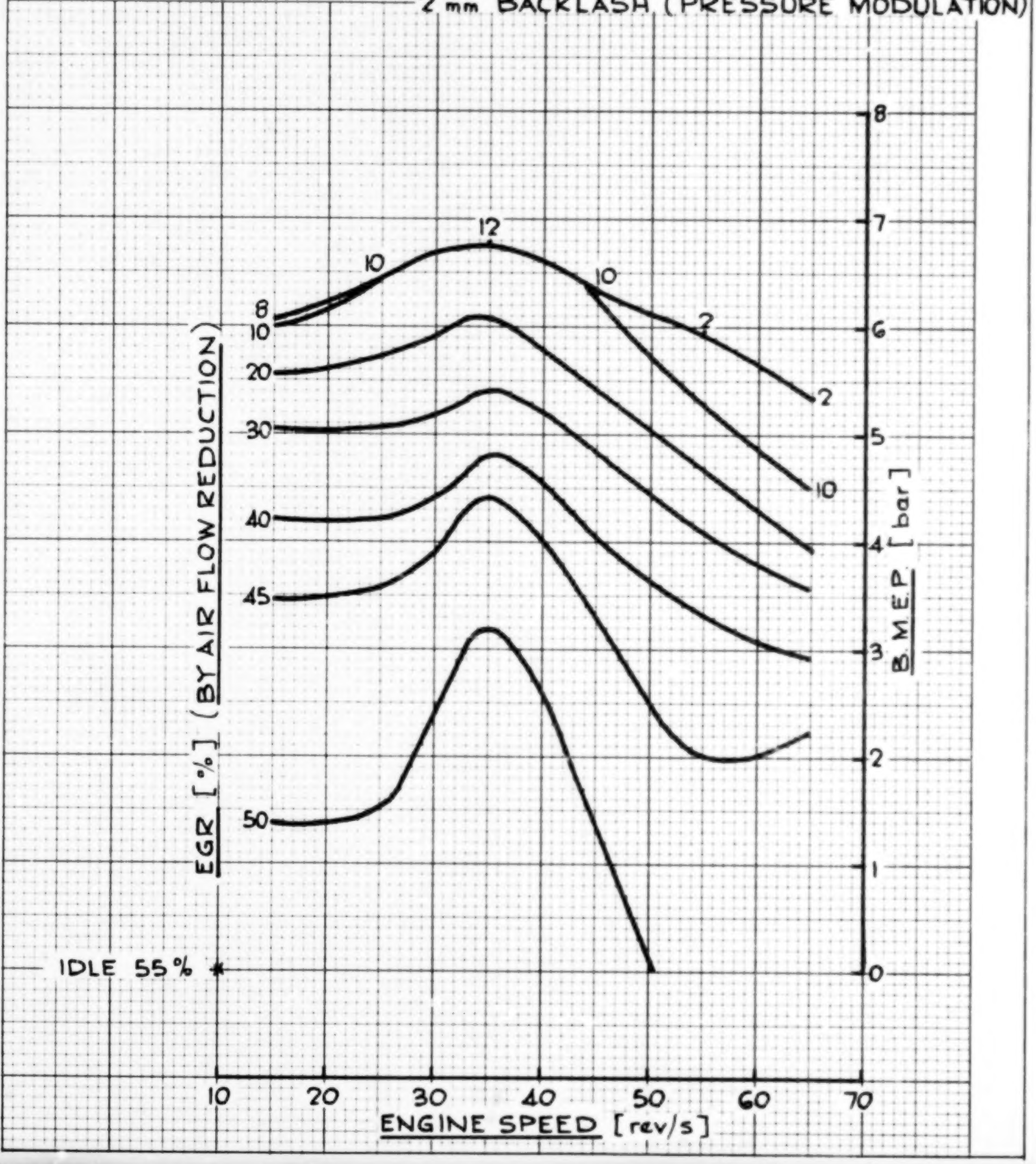
EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm X 92·4 mm X 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP SHOWING EGR MODULATION G
VALVE BUILD AS FOR MOD. F. BUT RETAINING SOME EGR
AT FULL LOAD

STATIC SETTINGS: 25·5 mm LIFT AT ZERO RACK
1·5 mm LIFT AT 100% RACK
2 mm BACKLASH (PRESSURE MODULATION)



RICARDO CONSULTING ENGINEERS

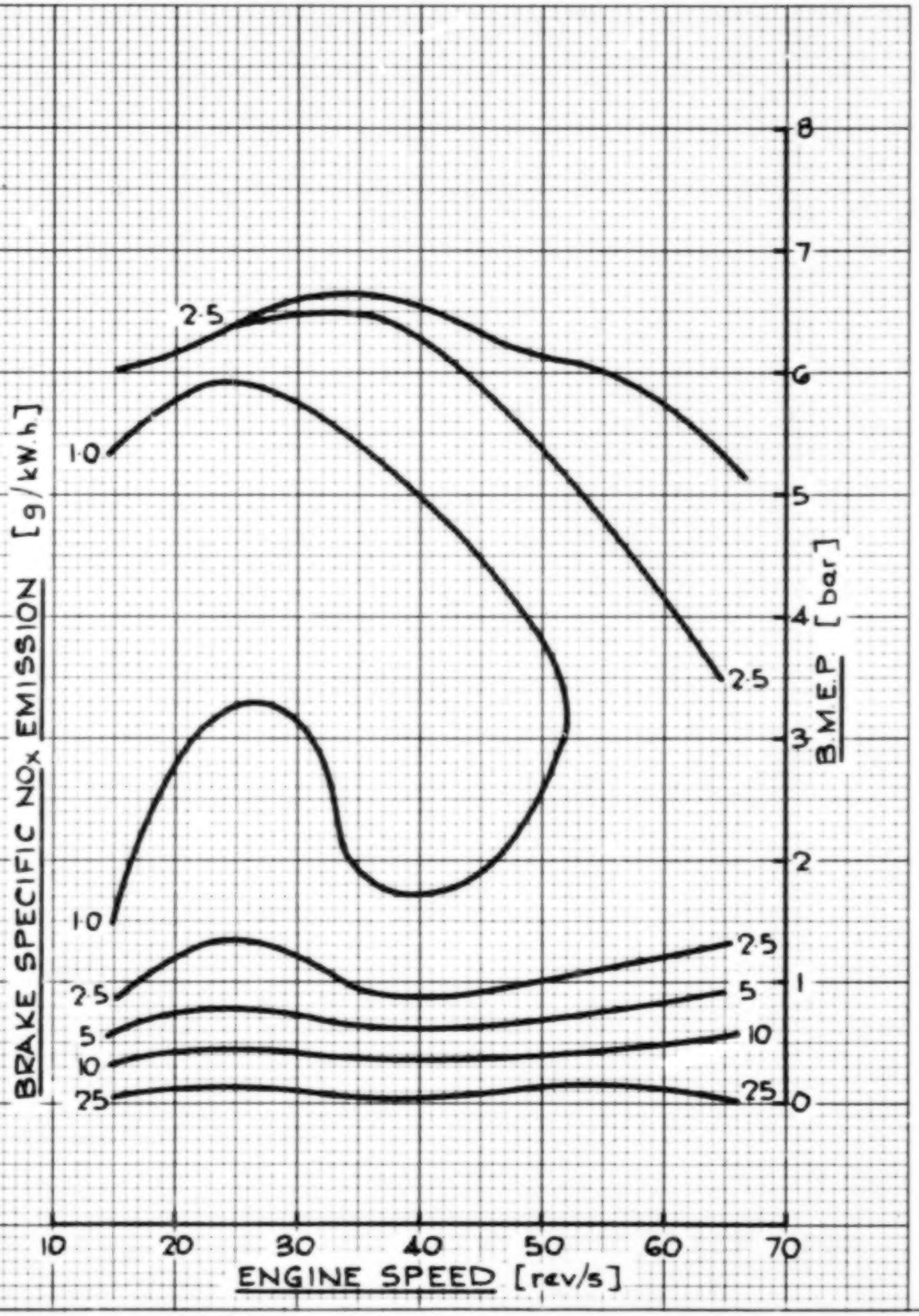
FIG. No. 154
Drg. No. D35044
Date FEB. '78
Engine Curve No. 208

EPA MODULATED EGR STUDY

MERCEDES OM 617 ENGINE 91 mm x 92·4 mm x 5 CYL

TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC NO_x EMISSION
BASED ON EGR MODULATION G

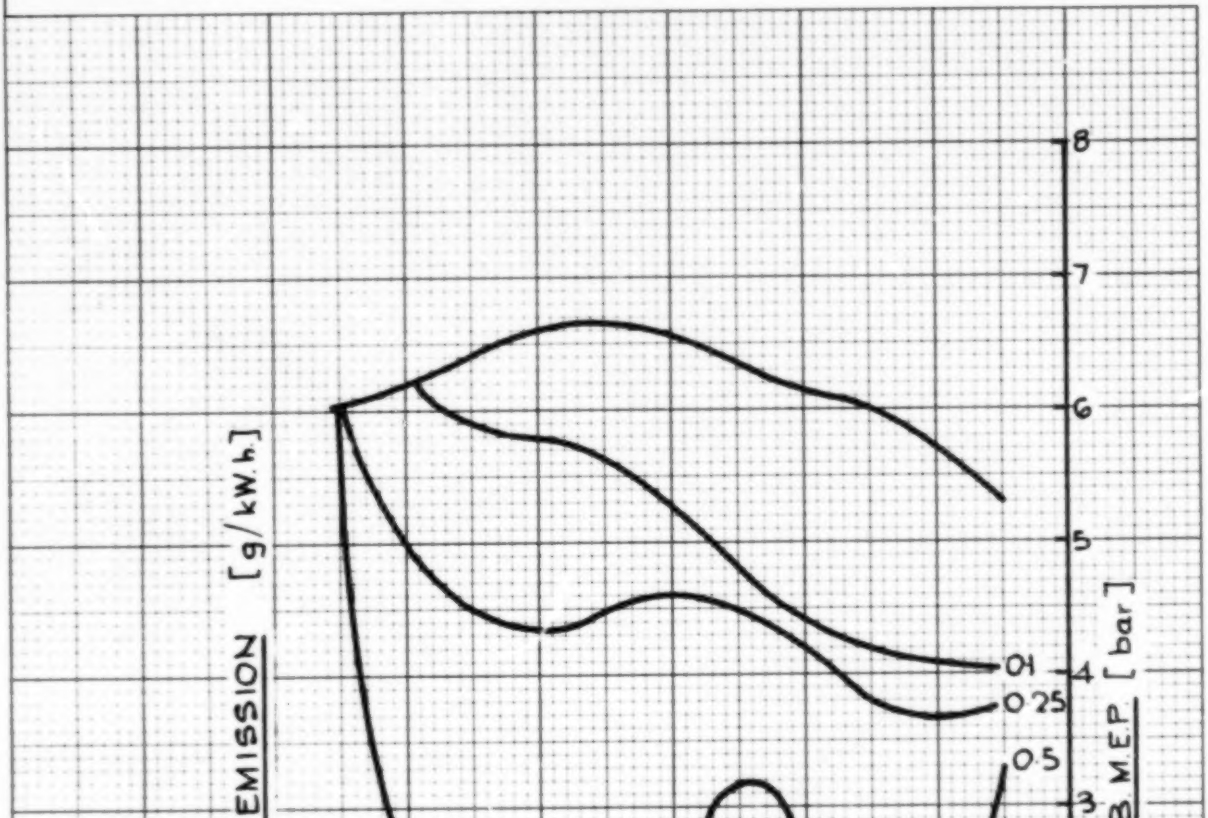


RICARDO CONSULTING ENGINEERS

FIG. No. 155
Drg. No. D35045
Date FEB.'78
Engine Curve No.180

EPA MODULATED EGR STUDY
MERCEDES OM617 ENGINE 91 mm × 92·4 mm × 5 CYL
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC HC EMISSION
BASED ON EGR MODULATION G

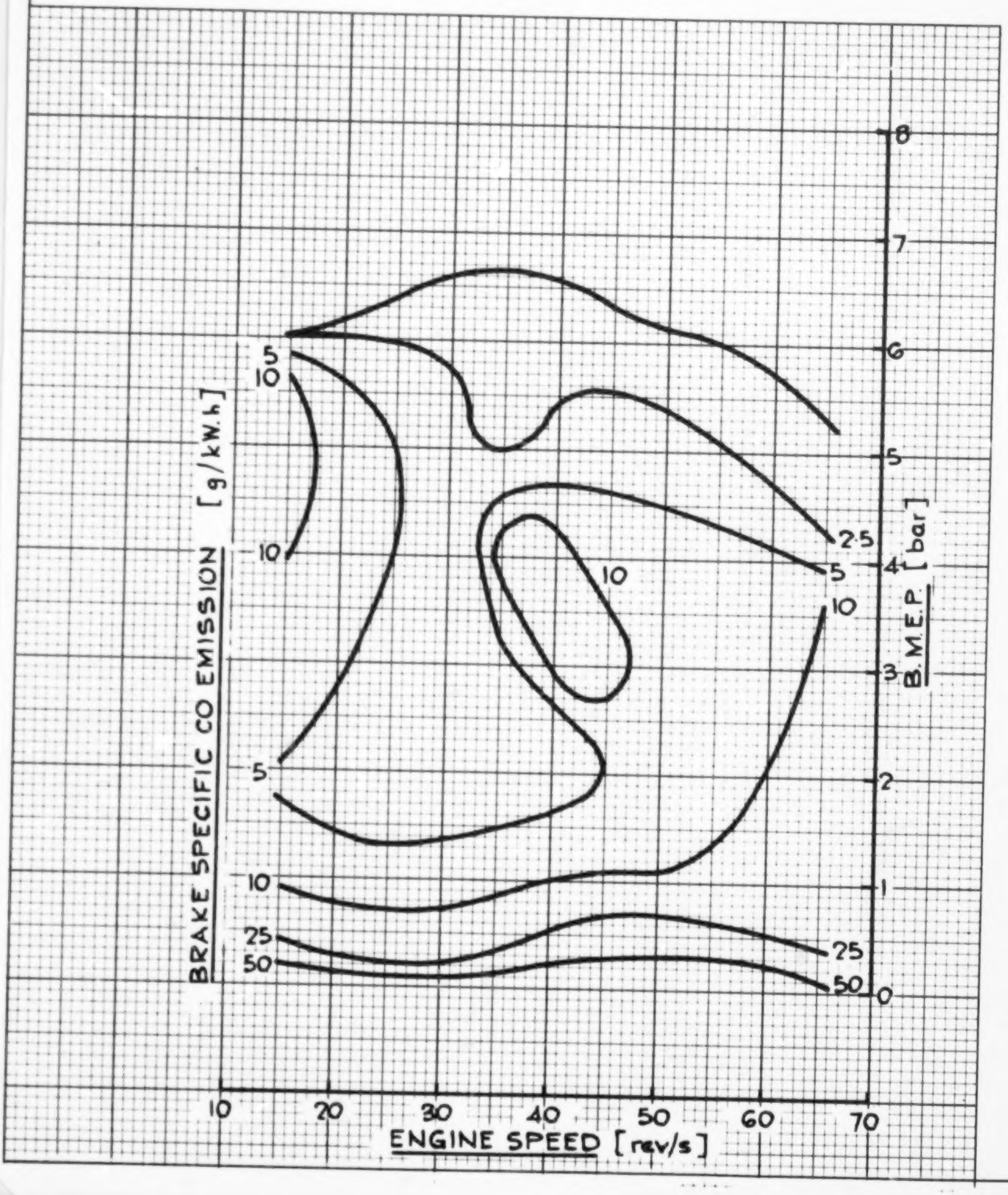


RICARDO CONSULTING ENGINEERS

FIG. No. 156
Drg. No. D35046
Date FEB. '78
Engine Curve No. 210

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91mm x 92·4mm x 5CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC CO EMISSION
BASED ON EGR MODULATION G

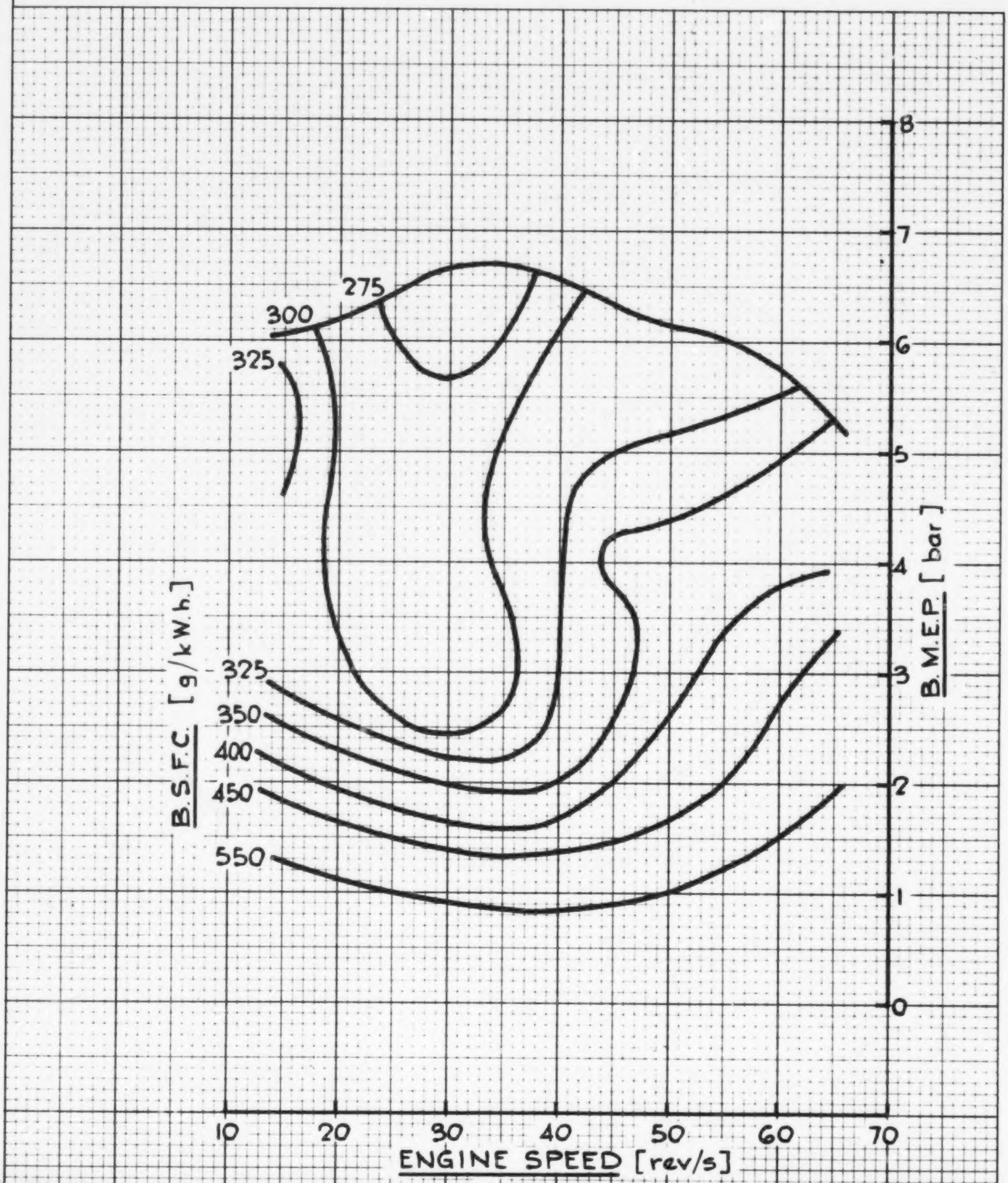


RICARDO CONSULTING ENGINEERS

FIG. No. 157
Drg. No. D35047
Date FEB '78
Engine Curve No. 212

EPA MODULATED EGR STUDY
MERCEDES OM 617 ENGINE 91 mm × 92·4 mm × 5CYL.
TURBOCHARGED BUILD

COMPOSITE MAP OF BRAKE SPECIFIC FUEL CONSUMPTION
BASED ON EGR MODULATION G



RICARDO CONSULTING ENGINEERS

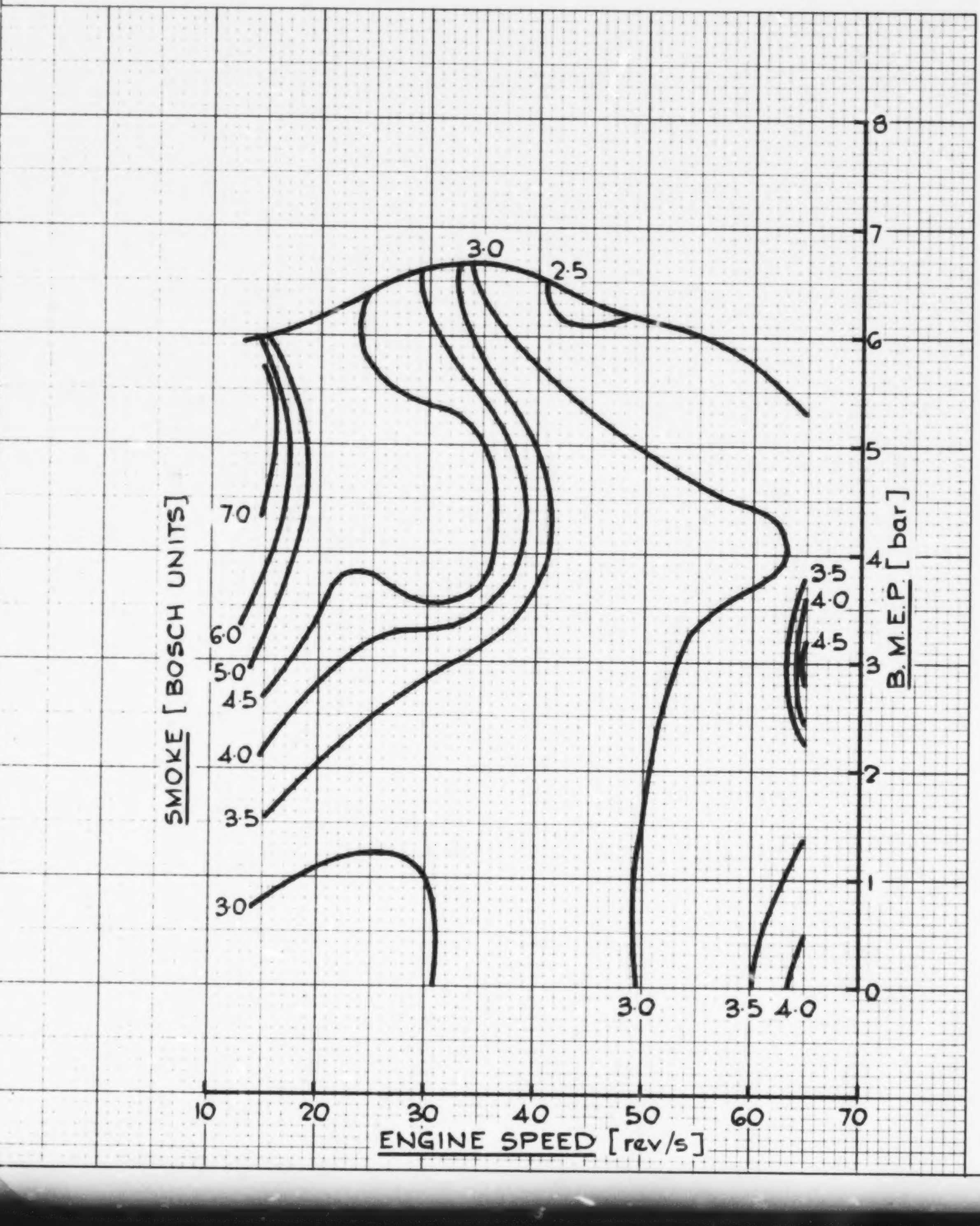
FIG. No. 158
Drg. No. D35048
Date FEB '78
Engine Curve No. 214

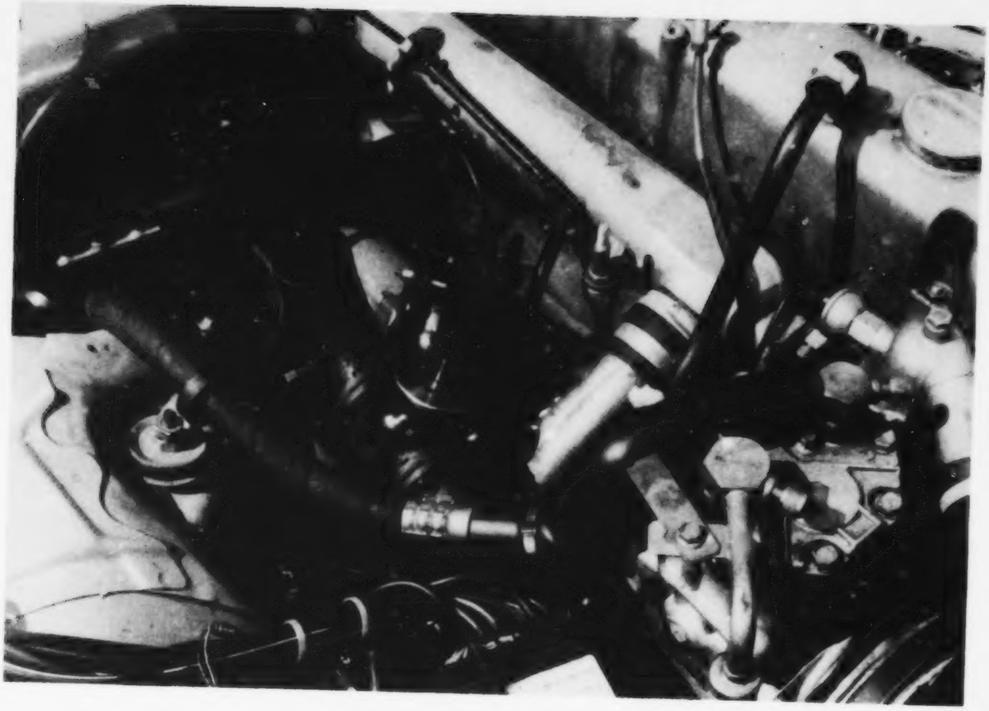
EPA MODULATED EGR STUDY

MERCEDES OM617 ENGINE 91 mm x 92·4 mm x 5 CYL.

TURBOCHARGED BUILD

COMPOSITE MAP OF EXHAUST SMOKE DENSITY
BASED ON EGR MODULATION G





Installation of EGR Valve in Vehicle

(Air Cleaner Removed)